CONCEPTIONS OF DESIGN IN A CULTURE OF SIMULATION

by
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Bachelor of Architecture. Cornell University, 1999
Master of Science in Architecture Studies. MIT, 2003

Submitted to the Department of Architecture in
Partial Fulfillment of the Requirements for the degree of

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Abstract

Design is a system of relationships in flux. Practitioners at Arup, a global design consultancy, negotiate a place for themselves within this system by using simulations to mediate their professional relationships. Simulations are spaces of exchange; they bridge between the technical domains of practitioners at Arup and the particular needs of their clients. Over the past sixty years, Arup has expanded into new domains of work by creating simulations to suit new audiences: architects, regulators, curators, developers, and insurers. For practitioners at Arup, simulations are pliable media for exploration, communication and professional positioning.

My study of simulation at Arup builds on a history of scholarship by writers like Lewis Mumford, Sherry Turkle, and Peter Galison, who examine how cultures define themselves through the technologies they use and the way they use them. My contribution to this discourse is to show how designers use simulations to establish the professional relationships and the conceptual distinctions that define their work. Through selected scenarios from the project history of Arup, this dissertation describes how simulations are used, not only to describe designs, but to construct conceptual distinctions, between the prescriptive knowledge of regulators and the performance-based knowledge of simulations; between the intent of form envisioned by architects, and its performance, articulated by engineers at Arup; and between the identity of the scientist and that of the designer, both strategically embraced by practitioners at Arup. These conceptual juxtapositions and others underlie efforts by practitioners at Arup to make a place for themselves in design.

My dissertation concludes with a reflection on an implicit metaphor in use at Arup, that simulation is a kind of theatre. By probing this metaphor, we can understand the practice of simulation as a balance between immersive and analytical ways of engaging audiences. Creating a valid simulation at Arup, like creating a successful theatrical performance, is all about connecting with your audience in the right way.

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Biography

Yanni Alexander Loukissas grew up in the United States and Greece. He earned a Bachelor of Architecture from Cornell University in 1999 and subsequently taught there from 2000 to 2001. In 2001, he started a Master of Science in Architecture Studies (SMArchS) at MIT in order to explore the architectural implications of combining scripting and digital fabrication. His master's thesis, entitled *Rulebuilding: Exploring Design Worlds through End-User Programming,* was funded by the MIT Center for Bits and Atoms and won the SMArchS thesis award. In 2003, he was accepted into the PhD program in Design and Computation as a Presidential Fellow. He worked closely with the MIT Initiative on Technology and Self in the Program on Science, Technology and Society. As part of the Initiative, he was a National Science Foundation Pre-doctoral Fellow on an interdisciplinary research project, *Information Technologies and Professional Identities: A Comparative Study of Virtuality,* from 2004 to 2005. The results of this project will be published in 2009 by the MIT Press in an volume entitled *Simulation and its Discontents,* edited by Sherry Turkle. He also taught sculpture at the School of the Museum of Fine Arts in Boston from 2004 to 2006 and worked with Small Design Firm from 2006 to 2008 on an art information system for the American Wing of the Metropolitan Museum of Art in New York City. He is currently a Visiting Lecturer in Architecture at Cornell University, where he teaches design theory and studio.

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This work was made possible by the help of many institutions, informants, collaborators, advisors, and family members, the boundaries among which became increasingly blurred over the past few years, as this dissertation became the focus of my intellectual and emotional life. A full list of these contributors would be impossible to compile. However, I wish to thank a few special individuals, those who had a profound influence on the final product.

I must first thank my informants, those who provided the "grist for my mill." In "Keepers of the Geometry," I have kept the names of my informants confidential, but I would like to express my gratitude to them. In my study of Arup, I owe special thanks to Jessica Strauss, a classmate from Cornell, who introduced me to key members of the firm and helped me earn their trust. I also wish to single out Mahadev Raman, the Director of the American offices of Arup, for championing my study before the Arup Board of Trustees and for guiding my initial round of interviews. I had many other important informants at Arup including but not limited to: Alban Bassuet, Ryan Biziorek, Raj Patel, Cecil Balmond, Tristan Simmonds, Richard Sturt, Alistair Guthrie, Chris Twinn, Steve Priddy, Mikkel Kragh, Darren Woolf, Chris Marion, Peter Bressington, Margaret Law, Neil McClelland, Graham Dodd, Scott Biondi, Alvise Simondetti, Tony Sheehan, Julian Diamond, Andrew Sedgwick, Steve Walker, Roger Chang, Alec Milton, Chris Kaethner, Jeremy Watson, Bob Lang, Tristram Carfrae, Matt Jackson, Matt Clark, Leo Argeris, David Scott, Dan Peterson, Robert Stava, Hussein Moussa, and Daniel Imade.

Among those who helped me from MIT, I must thank my committee members first. William Porter has been my closest advisor, interlocutor, and confidant during this work. I could not have asked for a more patient, wise and generous guide through the difficulties of doing a dissertation. Bill loves teaching, but also learning. It is rewarding to be his student, because you know that he is learning with you. Sherry Turkle has shaped the way that I think about technology and culture. She also inspired my interest in ethnography, taught me how to do it, and gave me the confidence to see this work through. William Mitchell opened both conceptual and real domains for me. He made many intellectual contributions to this work and helped to facilitate my stay at the University of Cambridge. Finally, Edith Ackermann has been a source of inspiration and insight since my first days at the institute. Over the past seven years, she helped me to see design through "her lenses," the lenses of social science. In addition, she convinced me that I could make a contribution to social science, using the lenses of design.

Furthermore, I wish to acknowledge the faculty and staff of the

Department of Architecture, the Media Lab, and the Program in Science Technology and Society at MIT for their many contributions to my education. In particular, I would like to thank Renee Caso, for guiding me over the administrative hurdles of the PhD; Terry Knight, Dennis Sheldon, and Sotirios Kotsopoulos for inviting me into their classrooms as a teaching assistant and as a collaborator; and George Stiny, the director of the PhD program in Design and Computation, for providing a model of intellectual rigor and achievement in his work, but encouraging his students to find academic fulfillment on their own terms. Additional thanks to the Department of Architecture at the University of Cambridge and to Churchill College. These institutions hosted me while I conducted fieldwork in England. Marcial Echenique and Koen Steemers helped me get past many of the guarded doors throughout Cambridge. William Fawcett, my informal advisor at Cambridge, and his wife, Di Haigh, were more than intellectual and cultural guides to my new environs; they were like family.

The students at MIT created a community that supported and challenged my work at every turn; I needed both. Amongst those who were not just friends and colleagues, but also close collaborators, I wish to thank Anas Alfaris, Saeed Arida, Daniel Cardoso, Stylianos Dritsas, Nick Gayeski, Mitchell Joachim, Axel Kilian, Josh Lobel, Robin MacGregor, Natasha Myers, and Alise Upitis.

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Finally, my family has provided crucial emotional support during my research and writing. My grandmother, Pauline Brotman, as well as my aunts, uncles and cousins offered continual encouragement. My sister, Jennifer Loukissas, and her husband Doug Lynott, have cheered me on with particular enthusiasm. In turn, I look forward to cheering on their newborn son, Michael, as he discovers the world in his own way. My mother, Randy Loukissas, has been an emotional anchor whenever the anxieties of completing this dissertation have threatened to overtake me. My father, Dr. Philippos Loukissas, has helped me maintain the necessary illusion that I have simply been following in his footsteps and that this dissertation was a *fait accompli.* Both my parents have been guiding models; without those particular models, I could never have finished this study. Mom and Dad, this dissertation is dedicated to you.

Contents

PRELUDE: KEEPERS OF THE GEOMETRY

This is an essay about architects in a culture of simulation, based on interviews I conducted between 2002 and 2005. I have studied architects and their collaborators in numerous professional and academic environments; this essay focuses on the stories of two organizations, addressed here through the pseudonyms Paul Morris Associates and Ralph Jerome Architects. These studies preceded my research on Arup and serve here as both a prelude to the themes that I will address in my writing on Arup and as a counterpoint.

Architects in a Culture of Simulation

"Why do we have to change? We've been building buildings for years without CATIA?" Roger Norfleet, a practicing architect in his thirties poses this question to Tim Quix, a generation older and an expert in CATIA, a computer-aided design tool developed by Dassault Systemes in the early 1980's for use by aerospace engineers.[1] It is 2005 and CATIA has just come into use at Paul Morris Associates, the thirty-person architecture firm in the Southwest where Norfleet works; he is struggling with what it will mean for him, for his firm, for his profession. Computer-aided design is about creativity, but also about jurisdiction, about who controls the design process.

[1] CATIA is an acronym for "Computer Aided Three Dimensional Interactive Application."

Figure 1. Perspective machine, Albrecht Dürer, *Unterweisung der Messung mit dem Zirkel und Richtscheit*, (Dietikon-Zürich, Verlag Stocker-Schmid, 1966).

Architectural theorist Dana Cuff writes that each generation of architects is educated to understand what constitutes a creative act and who in the system of their profession is empowered to use it and at what time.[2] Creativity is socially constructed and Norfleet is coming of age as an architect in a time of technological but also social transition. He must come to terms with the increasingly complex computer-aided design tools that have changed both creativity and the rules by which it can operate.

Traditionally, architecture has been defined by its practitioners and patrons in relation to three sets of standards: technical, economic, and aesthetic. Buildings must be sound, practical, and beautiful. Vitruvius, author of one of the earliest known architectural treatises, *De Architectura*, expressed these qualities in Latin

[2] Dana Cuff, *Architecture: The Story of Practice* (Cambridge, MA: MIT Press, 1991).

as *irmitas*, *utilitas*, and *venustas*. Modern architects have maintained distance from technical and economic activities in order to privilege their aesthetic role, what the sociologist Magali Sarfatti Larson has called the "aesthetics of construction."[3] However, with new technologies of simulation, embodied by programs such as CATIA, things are changing; new forms of technical expertise are becoming central to the architect's professional identity.

In today's practices, architects use computer-aided design software to produce three-dimensional geometric models. Sometimes they use off-the-shelf commercial software like CATIA, sometimes they customize this software through plug-ins and macros, sometimes they work with software that they have themselves programmed. And yet, conforming to Larson's ideas that they claim the higher ground by identifying with art and not with science, contemporary architects do not often use the term "simulation." Rather, they have held onto traditional terms such as "modeling" to describe the buzz of new activity with digital technology. But whether or not they use the term, simulation is creating new architectural identities and transforming relationships among a range of design collaborators: masters and apprentices, students and teachers, technical experts and virtuoso programmers. These days, constructing an identity as an architect requires that one define oneself in relation to simulation.[4] Case studies, primarily from two architectural firms, illustrate the transformation of traditional relationships, in particular that of master and apprentice, and the emergence of new roles, including a new professional identity, "keeper of the geometry,"

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[3] Magali Sarfatti Larson, *Behind the Postmodern Facade: Architectural Change in Late Twentieth-Century America* (Berkeley: University of California, 1993).

[4] Individual architects will, of course, have different personal styles of relating to computation. My analysis here is at the intersection of artifact, personal style, and culturally available roles within the profession. See Sherry Turkle and Seymour Papert, "Epistemological Pluralism and the Revaluation of the Concrete," *Signs* 16, no.1 (Autumn, 1990), 128-157.

defined by the fusion of person and machine.[5]

Paul Morris Associates

Little more than a year ago, Paul Morris hired Quix to teach architects how CATIA might be used to rigorously model their designs in three dimensions. Although Quix was never trained in architecture, he has been working in the field for almost two decades. Quix once taught and sold CATIA to its intended users in the aerospace industry, working primarily as an employee of IBM, the parent company of Dassault Systemes. Now in middle age, Quix is using his expertise in CATIA to create a role for himself in architecture, a field he flirted with briefly as a young man, but turned away from to pursue his fascination with computer-aided design. Quix is teaching CATIA at Paul Morris Associates and also working to apply the software to the firm's current projects. At Paul Morris, there is active resistance to his presence. Control over CATIA translates into a great deal of control indeed. Before designs are built, they only exist as representations; whoever models a project produces and controls the current reality of the design.

At Paul Morris Associates, resistance to CATIA is shaped by many considerations. Rikle Shales, an architect in her mid thirties, resists putting designs into CATIA because she says that once they are thus represented, people tend to see the designs as frozen, as a done deal. She points to the number of design changes that take place in an ongoing project and argues for keeping designs out of CATIA until late in the process. She says, "Quix has a habit of thinking that if we just put things into CATIA, they will be done and coordinated. It's pointless to model the current design in CATIA when it is almost certain to

[5] In the office of Paul Morris Associates, the responsibility for coordinating all of the geometric modeling work on a given project falls upon one architect, referred to by his peers as the "keeper of the geometry."

change." Her position is well reasoned, but she and the architects around her know that it has a political dimension. Keeping designs off CATIA lets her stay in greater control of the design process. Once within CATIA, one might say that all designs belong to Quix because he is the one best positioned to manipulate them.

Quix and his architect opponents define themselves in relation to CATIA and one another. From Quix's perspective, architecture needs CATIA, which can bring a new rigor to building. He reasons that architects have difficulty learning CATIA because it requires a "level of rigor that architects are not used to." His colleagues' resistance to CATIA reinforces his sense of being different from those around him; he is the one who is a rigorous engineer.

Indeed, Quix describes his life at Paul Morris Associates in terms of "three difficult phases," each a stage that includes some resistance to CATIA. He calls the first phase "the brick wall." In this phase, he says, architects complain that they are too busy to learn. They say that the program is foreign; it feels like somebody else's approach to architecture. Quix refers to this first phase as "a sickness called NIH (Not Invented Here)." In the brick wall phase, Quix is isolated.

A second phase begins when Paul Morris, the founding principal of the firm, actually orders a team of architects to learn CATIA, with Quix as their tutor. Quix teaches the practitioners one-by-one. In this second phase, call it tutelage with resistance, CATIA is viewed very differently by the practitioners and their teacher. Quix sees CATIA as a new way of looking at the world, a systematic and three-dimensional way of approaching design. Most centrally, it is a new way of being an architect. Quix feels he is bringing more than a new piece of software to Paul Morris Associates. He is bringing its architects a new epistemology and a new identity.

For the designers who are his students, CATIA is simply a technique, one more skill set to apply to their practical problems. The conflict between Quix and the architects of Paul Morris Associates calls to mind Sherry Turkle's description of two ways in which technology can be "transparent."[6] A "modernist" transparency enables a user to gain access to the inside workings of a system. It evokes the aesthetic of early relationships with cars in which one could "open the hood and see inside." This is the kind of relationship to CATIA that Quix desires. Turkle contrasts this with the "Macintosh meaning" of the word transparency. This is a transparency that reverses the traditional definition. It says that something is transparent not if you know how to make it work but if you can use it without knowing how it works. It is the transparency of the user who navigates the surface of the system, but does not have access to underlying mechanisms. Its aesthetics are postmodern. This is the understanding of technology that interests many of Quix's students.

Robert Laird, an architect in his early thirties, is someone who Quix considers something of a protégé. Laird has mastered working on the "surface" of CATIA. Laird has been using three-dimensional modeling programs since his years as an undergraduate majoring in architecture, AutoCAD, 3D Studio MAX, Rhinoceros, Form-Z, and has complaints about all of these platforms. For example, he says, "Rhino is like 3D for dummies." "FormZ produces gaps or leaks." Laird sees CATIA as the system that finally gets things "right." "It does everything you need." Laird puts confidence in CATIA without a deep technical understanding of how it works. "CATIA gives me the feeling that I have control when I use it... Other systems will only get to a certain point before crashing, not CATIA." Laird claims that he was hired at Paul Morris Associates because of his skill with computer-aided design. Often, he works exclusively on the computer or coordinates the computer-aided design work done by others, a role he and his peers call being the "keeper of the geometry."

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[6] See Sherry Turkle, *Life on the Screen: Identity in the Age of the Internet* (New York: Simon and Schuster, 1995).

Laird's professional identity is constructed around his relationship with computer-aided design. Although Laird has become Quix's best student with CATIA, he continues to see the software in his own way. Quix teaches CATIA as a means of establishing technical control over designs. However, in Laird's hands, CATIA "feels artistic." For Laird, CATIA is a medium "for the manipulation of light and shadow."

A third phase of Quix's teaching is comprised of implementation with continuing resistance. In phrase three, designers at Paul Morris use CATIA (with Tim Q's tutelage) for the design of a large project, a major public building. By this stage, the designers feel that using CATIA makes them part of the evolving direction of the firm. Yet, even at this point, resistance to CATIA continues, although it takes new forms. For example, despite his affection for CATIA, Laird has reservations about its practicality. He complains that it is not architects but consultants and contractors who are its main beneficiaries: "It is focused on making someone *else's* job easier." Laird is concerned that at Paul Morris Associates, people spend too much time modeling buildings on computers. "We are dumping hours in modeling." Laird's position is echoed by a senior designer who says that computer-aided design increases architects' tendency to "fetishize drawing" and create too many details too soon in the design process. Even with CATIA's use mandated by the head of the firm, Quix is still on the defensive.

Indeed, within the firm, Rikle Shales, has carved out her identity by avoiding CATIA altogether. In architecture school, Shales was something of a computer guru. She was the "go-to person" for other students. But in Paul Morris's office, Shales keeps her knowledge of modeling to herself. When she works on the computer, she sticks to two-dimensional programs; mostly, she communicates her ideas through sketches. Morris specifically asked her to learn CATIA, but Shales never got around to it, something she explains as due to the weight of other responsibilities. Shales voices some regret about not learning the program. She says, "I like to feel that I am keeping up with everything," but in fact, Shales's authority over the public building project that "lives" on CATIA has been due, at least in part, to the fact that she has not learned system. The time she has saved has freed her up to do project administration. Beyond this, not knowing CATIA has confirmed her with a non-technical identity; she is seen as a people person and design person. Others describe her as the "glue" that holds projects together, organizes tasks within the firm, and coordinates communication with outside consultants.

While Quix and Laird forged their roles within the firm by identifying themselves with technology, Shales made her place by keeping it at arm's length. Paul Morris, the head of the firm has done neither. He does not represent himself as a technical expert, but has allowed the technology to be an active player in his relationships with colleagues, most notably his relationship with a younger generation.

When the first American architectural practices emerged in the nineteenth century, the master architect was an active participant in every aspect of his office's work.7 Theorists Donald Schön and Dana Cuff write about the strong master-apprentice relationship that developed in this context. Each argues, in their own way, that design is often best understood through a relationship between individuals, the master and apprentice. Dana Cuff writes that this is the "principle social relation" in architecture.8 Schön describes traditional design education through the intimate involvement of a master architect, Quist, in all the particulars of Petra, his student's work. Schön illustrates how closely they work together, with Quist's hands on Petra's drawings:

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[7] In the highly influential office of H.H. Richardson, Richardson himself played the parts of a manager and a model of practice. Richardson was among the first American architects trained at the Ecole des Beaux-Arts in Paris. At the time, there was no such institution in America. Therefore, Richardson took it upon himself to combine training with practice in his office.

[8] See Cuff, Architecture, and Donald A. Schön, The Reflective Practitioner: How Professionals Think in Action (New York: Basic Books, 1983).

> Quist places a sheet of tracing paper over Petra's sketches and begins to draw over her drawing. As he draws he talks. He says, for example, "the kindergarten might go here ... then you might carry the gallery level through -- and look down into here . . ."[9]

At Paul Morris Associates, computer-aided design software is reconfiguring the master-apprentice relationship. Paul Morris is a prolific practitioner and retired academic in his late sixties who gained early acclaim for his striking modernist buildings. He belongs to a generation of which architectural theorist Reyner Banham writes, "Being unable to think without drawing had become the true mark of one fully socialized into the profession of architecture."[10] Morris still relies on a pencil to develop new ideas. However, within his office, computer modeling is replacing many of the traditional tasks of the pencil, such as drafting and rendering. And although Morris rarely touches the machine, it has transformed his personal practice as well. He often works on the concept phase of designs with an apprentice, a younger employee who can help him model a range of design ideas.

Drew Thorndike is one of the apprentices who work with Morris to prepare sketches for design competitions. Thorndike has worked with computer-aided design since he was in college and continues to spend time learning new software. When asked about how design software figures in his long-term goals, Thorndike replies eagerly that they play "a big part. . . .I want to stay ahead of the game. . . Computers equal speed and if I don't learn the new software, I will be out of the market. I am convinced of that."

[9] Schön, *The Reflective Practitioner*, 80.
[10] Reyner Banham, "A Black Box: The Secret Profession of Architecture," in *A Critic Writes: Selected Essays by Reyner Banham* (Berkeley: University of California Press, 1996).

From their first interactions on a project, a pattern emerges: Morris makes a sketch and Thorndike translates the sketch into a geometric model on the computer. Morris always asks Thorndike to print out the computer images he has generated. Then, Morris and Thorndike sit together with a roll of tracing paper and, in a close variant to the practice of Quist and Petra that Schön writes about, Morris draws revisions over Thorndike's prints.

Over time, Morris stops requesting prints and begins to look directly at the images on the computer. Now it is not unusual to hear Morris say to Thorndike, "Let's go look at your computer." The concept sketches are still drawn by Morris, but as projects progress, he and Thorndike work together at the computer; Thorndike operates the machine while Morris gives him guidance. From Thorndike's point of view, his boss has "learned to accept the technology on his own terms." From the point of view of other employees, Morris has conceded an important role, or as one puts it, "He is no longer the one 'sculpting space.'" But Morris has maintained what was most important to him. He wants to stay in touch with the evolving model no matter where it is, even if he has to sacrifice some of the physical intimacy he has with pencil drawings.

As they work, Morris and Thorndike are looking at the same screen, but they are not seeing the same thing. For example, when Morris makes a sketch for a new public library, Thorndike's job at the computer is to translate it into a modeling program called Rhinoceros, but which he affectionately refers to as "Rhino." Thorndike usually sits at the computer while Morris stands behind him. Rhino presents them with the virtual equivalent of a blank sheet of paper, a faint Cartesian grid floating in boundless space. With a click of the mouse, Thorndike chooses a starting point for an arc defined by three points on its circumference. Next, he chooses a section of an ellipse. With these two design elements, Thorndike generates a curved surface for the library's façade. Thorndike is choosing from a predefined set of shapes that the computer knows. These are his "primitives." Morris is watching his design emerge; he does not see into Rhino's inner world.

Rhino produces each of its images by simulating thousands of rays of light that reflect off primitives in the model and penetrate a virtual "camera," a virtual eye. This technique, known as "ray tracing," is based on an early Renaissance mechanism for transferring three-dimensional objects onto a flat surface. So, for example, when Thorndike rotates the screen model, Rhino actually computes a new camera position for the ray tracing algorithm. Thorndike understands how the image is being produced. Morris sees only the rotation and only the final image.

Morris is aware of the principles that drive Rhino's renderings. But when they talk about what is on the screen, Thorndike can make reference to details of Rhino's primitives and the ray tracing algorithm. Morris can only talk about lines, surfaces, and colors, at best a snapshot of the design. Before the technology intervened, Morris worked with images on paper, which he could physically manipulate. Now, his apprentice has a more direct experience of the developing design. Morris's experience is mediated, dependent.

Maurice Merleau-Ponty suggests that people incorporate instruments into their physical sensibilities through the experience of manipulating them.[11] From this point of view, Morris and Thorndike have a different experience and therefore a different understanding of the model. Morris's is more distant, Thorndike's more embodied and internal.

Thorndike is proud of his expertise with Rhino and other modeling software. He says, "I've taken AutoCAD to the limit. People in the office are often surprised by what I can do with the program." Yet he, like his mentor, still thinks with a pencil. Thorndike describes the evolving design for the library that he is modeling under the guidance of Morris: "The room is an elongated almond. .

[11] Merleau-Ponty, *Phenomenology of Perception* (New York: Routledge, 2002).

. The entrance is tight and tall and the center of the space is wide but the same height." As Thorndike speaks, he takes a thick dark pencil out of his pocket and draws the profile of the library onto the bare surface of one of the drafting tables. His identity as an architect, like that of his master, lies between technological worlds.

When Thorndike becomes frustrated with Rhinoceros, when he reaches a limit, he turns to other modeling solutions. He is currently producing a new model for the library with AutoCAD. The AutoCAD model has qualities like repetition and flat surfaces that make it easier to build, both virtually and physically. Thorndike explains that the warped surfaces used in Rhino would be very expensive to build, especially in glass. In order to model the library in AutoCAD, the design had to be simplified, recast in a "platonic" geometry. In fact, AutoCAD could not handle the "warped" geometry used in Rhino. In other words, the latest version of the building was not just designed in AutoCAD, it was designed *for* AutoCAD.

Thorndike's decision to turn to AutoCAD was as much about preserving his creative role on the project as it was about making a design that conformed to the firm's ideals and was a rational use of resources for the client. He could have asked another architect to do the work that he could not do with Rhino, but unlike Shales and Morris, Thorndike is carving out his identity in the firm by learning new computer applications. He says that asking others to make a geometric model for you takes longer. He does not directly say that it makes you dependent on them, but this thought is present in everything he says. "First of all, you have to wait for that person to become available. Then you have to explain the whole project to them. Lastly, if you want to hold their interest, you have to give them something significant to work on. I would rather do it myself." In the course of working on this project, Thorndike improves his ability to move back and forth between warped geometries in Rhino and platonic geometries in AutoCAD. After one weekend he says, "Me and technology worked together this weekend."

Thorndike feels strongly that learning Rhino will help him extend his role in developing competition work with Morris. However, he has worked in the office for twelve years and knows that within the Paul Morris office, his role in design will only extend so far. Eventually, he wants to venture out on his own. For Thorndike, working at Paul Morris is an opportunity not only to learn about design but about the mechanics of owning a firm and managing projects. For Thorndike, skill at geometric modeling enables him to negotiate a role in the office, a "chip" that provides access to certain tasks. However, Thorndike stresses that for his long-term development, other skills, such as project development, may be equally or more important for him. He must continually negotiate his roles as designer, simulations expert, and manager in order to assure a creative role for himself in contemporary practice.

Ralph Jerome Architects

Ralph Jerome Architects, a hundred-person office in the Midwest, uses CATIA to realize complex projects that require it to manage the knowledge of many partnering disciplines. Here, CATIA serves as a "place" where many different kinds of knowledge meet. The details of construction are often contributed by consultants and fabricators. CATIA brings together knowledge of construction materials from outside collaborators with schematic information about designs. Ralph Jerome stresses that for him, this technology brings the architect closer to the craftsperson who will actually handle the materials of construction. He sees CATIA as a way to bypass the many layers between sketch and final building. However, at Ralph Jerome Architects the reconfiguration of work around CATIA has also led to confusion, redundancy, and loss of data, problems that are common when working with digital files. These developments have prompted the establishment of a new role. Like Paul Morris, Ralph Jerome needs a "keeper of the geometry," someone to play a role similar to, but more powerful than that of Robert Laird at Ralph Jerome's firm, this role has a formal title, "Director of Computing." Malcolm Deitrich has this role and is responsible for coordinating the geometric modeling work in the office.

For Deitrich, the computer is on its way to becoming the unifying collaborative space for designers and technicians. In Deitrich's vision, one person is at the center of the building process whose power comes from access to knowledge, all of which is in the computer. Deitrich describes this person as a "master techie-enabled architect sitting in the middle."

As Deitrich envisages it, the techie-enabled architect has the potential to crystallize a new kind of integration among members of the firm and external contractors. The techie-enabled architect understands every bolt in the building and can see and coordinate the work of every person involved. Deitrich looks forward to the day when he will be able to say, "I understand what this shape is and how it's built and how pieces go together and I can validate and I can stand up and say this thing will work." On one level, the architect at the center is all-powerful; yet there is a paradox in Deitrich's vision. In this model, craftsmen are given a more creative role in design and sometimes Deitrich talks about himself as "just stitching the bits together." Being in control of the machine can seem like low-level work, "Sometimes I feel I'm just a full time translator."

Technological Roles: From Trading Zones to Communications Media

In the stories of these architects we see a variety of responses to technology and a variety of emerging identities. Quix is a new breed of expert technician; Shales defines herself by her refusal to participate in the demands of technology; Morris and Thorndike are forging a new dynamic for master and apprentice in a culture of simulation; Deitrich provides a glimpse of the architect on the verge of becoming cyborg, an identity that requires becoming one with the machine.

There are elements of Deitrich's vision that already are at work at Ralph Jerome Architects. For example, Dimitri Kabel, an architect at the firm, "captures" in CATIA the specific physical knowledge that fabricators bring to the design process. For Kabel, working with computer simulation has made him see the whole of architecture as being about simulation, something that was not clear to him when representations were done with pencil and paper. When a project needs special technical knowledge about a suspended glass wall, Kabel works with a curtain wall consultant to model this knowledge in CATIA; the geometric model serves as a communications medium within the office. Yet, when the consultant is asked, for example, to codify his conventions for working with glass, the current limitations of Deitrich's vision become clear. The process of fabricating this curtain wall cannot yet be described in a form that can be modeled in CATIA. Deitrich laments that "one of the hardest things is going to a fabricator and telling them, provide us with your rules; what are the rules that we need to adhere to make this thing buildable?"

In these stories we see that the question, "Who am I in relation to software?" has become central to how architects negotiate professional identity. Paul Morris and Ralph Jerome use it as a tool to make buildings in partnership with computationally-savvy colleagues. But some architects are primarily masters of the virtual, securing international reputations in architectural competitions through objects that exist only on the screen. Their practices flourish on computers and in art galleries rather than on construction sites. Among them are architects who work with master programmers who are sometimes also architects.

Such is the relationship between Craig Haig and Mike Orlov, both of whom work in an academic setting. Haig understands how the program operates, has a working model of its underlying operation, but cannot program the simulations that make his work possible. This role falls to Orlov, "his" master programmer. Haig is master of a realm he cannot completely enter. Orlov says of their partnership: "It's really funny, while we are communicating together about the same thing, we are talking about different levels of the same thing."

Here, as in other relationships among architects who approach geometric modeling with different levels of understanding, the technology acts as what historian of science Peter Galison has termed a "trading zone." Galison uses the term to describe how those who belong to different social groups can productively trade objects and information without having the same understanding of the exchange.[12] But it is an apt description of how architects work across their own cultural divides whether it is Morris, the master, and Thorndike, the apprentice, or Haig, the virtual architect, and Orlov, his hacker partner.

Galison's terminology stresses the diversity in what different architects bring to negotiations with technology; another way to look at their exchanges is to stress similarities in what the software imposes on all of them. A program such as CATIA embodies culturally specific views of image making. These will be transmitted to any user who engages with the program; that user will be drawn into the embrace not just of a specific program but of a way of encoding reality.[13] Architectural theorist, William Mitchell talks of software as "frozen ideology."[14] Sociologist Gary Downey describes the power of computer-aided design as the

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[12] Peter Galison, Image and Logic (Chicago: University of Chicago Press, 1997), ch. 9.
[13] Diana Forsythe, Studying Those Who Study Us: An Anthropologist in the World of Artificial Intelligence (Stanford: Stanford University Press, 2001), Lucille Alice Suchman, Plans and Situated Actions: The Problem of Human-Machine Communication (Cambridge [Cambridgeshire]; New York: Cambridge University Press, 1987).
[14] The phrase "frozen ideology" was used by William Mitchell in a personal conversation I had with him in 2005.

subordination of design to computer graphics, a process in which one's eyes and fingers are given over to the machine.[15] In Michel Foucault's language, the program becomes a new kind of power, a force that "produces reality; it produces domains of objects and rituals of truth."[16] This is what Quix recognizes when he speaks of CATIA as more than a program, but as a way of seeing the world.

Like any profession, architecture may be seen as a system in flux.[17] However, with their new roles and relationships, architects are learning that the fight for professional jurisdiction is increasingly for jurisdiction over simulation. Computer-aided design is changing professional patterns of production in architecture, the very way in which professionals compete with each other by making new claims to knowledge. Even today, employees at Paul Morris squabble about the role that simulation software should play in the office. Among other things, they fight about the role it should play in promotion and firm hierarchy. They bicker about the selection of new simulation software, knowing that choosing software implies greater power for those who are expert in it.

As we have seen, sharing a screen does not necessarily mean sharing a vision. It does bring, however, a new kind of intimacy that makes explicit what is shared and what is not. For even when software is celebrated and used creatively, certain former habits of mind endure. In particular, architects remain preoccupied with drawing, the expression of another kind of intimacy with volume and profile.

Thorndike, the apprentice, believes Paul Morris hired him not for his technical expertise but for his ability to draw with a pencil. For Morris himself, who thinks with a pencil and is newly bound to an apprentice who can help him think on the screen, there are already intimations of a convergence. He has, after

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15 Gary Lee Downey, *The Machine in Me: An Anthropologist Sits Among Computer Engineers* (New York: Routledge, 1998).

16 Michel Foucault, Discipline and Punish: The Birth of the Prison, 2nd Vintage Books ed. (New York: Vintage Books, 1995), 94.

17 Andrew Abbott, *The System of Professions: An Essay on the Division of Expert Labor* (Chicago: University of Chicago Press, 1988).

all, chosen a working partner who is both fluent on the screen and with a pencil. In an instrumental sense, it is Thorndike's ability with a computer program that makes him indispensable to Morris, but it is Thorndike's fluency with a pencil that probably makes Morris comfortable with him as a colleague.

Quix, the CATIA expert, has had the opportunity to work with both firms discussed in this essay. He sees Paul Morris and Ralph Jerome as accepting new technologies in different ways, both for their firms and for themselves. Morris is more personally receptive to the computer. When it comes to the machine, Quix says that "[Paul Morris] is better at looking." In contrast, Ralph Jerome, keenly aware and a bit wary of the power of the technology on which his office is making its reputation, refuses to look at his designs on the screen. He says it is like "putting his hand in the flame." Morris, Jerome and those who work with them are in a continual struggle to define the creative roles that can bring them professional acceptance and greater control over design. New technologies for computer-aided design do not change this reality, they become players in it.

INTRODUCTION: SOCIO-TECHNICAL STUDIES AT ARUP

A Culture of Simulation

This is a study of simulations and the practitioners who use them in the context a new design culture developing around information technologies. Over the last few decades, information technologies for finite element analysis, ray-tracing, and computational fluid dynamics have been adopted by design practitioners to make new claims about acoustics, structures, airflow, and other design concerns in buildings. Many designers have reflected on these developments.[18] However, they have done so in terms that are primarily instrumental. In this dissertation, I will illustrate how information technologies for simulation are catalyzing new conceptions of design in the discourse of practitioners. If we are to understand the condition of contemporary design practice, we should consider the possibility that new practices of simulation are reshaping the meaning of design.

Practitioners in the emerging culture of simulation characterize their work and themselves in novel ways. They use simulated measures of building performance to supplement traditional prescriptive ways of knowing, implicit in building regulations. Along with the concept of building performance, design practitioners have embraced a conditional notion of knowledge. Their knowledge

[18] Among the most well known treatises on the use of simulation in design is: Herbert Simon, *Sciences of the Artificial* (Cambridge: MIT Press, 1996).

is no longer limited to known building forms. In the new culture of simulation, novel forms can be evaluated using a variety of simulated performance measures. Design practitioners are using these measures to overturn building regulations and delineate a new range of acceptable forms. Simulated performance measures are not limited to the analysis of material effects, like structures, acoustics, and airflow. Through virtual reality, design practitioners are beginning to simulate human experience in buildings. The social interactions between design practitioners are also framed in a variety of new ways by information technologies for simulation. New roles and relationships are emerging. Practitioners are using their skill with simulations to challenge traditional professional identities like "architect" and "engineer."

Design practitioners have adopted information technologies without necessarily giving up all their traditional methods of representation. They generate and share design options in digital models of buildings as well as physical models. They analyze designs using digital measures of building performance as well as material experiments. They develop professional experience and intuition through virtual reality as well as through experiences of real buildings. While traditional methods of representation have not disappeared, they have been swept up in a new culture of simulation, governed by new design discourses.

Design has always been a culture of simulation, but simulation has not always been digital or even numerical. Filippo Brunelleschi, an Italian Renaissance architect, invented perspective geometry to simulate the visual perception of space. In the eighteenth century, European architects like Pierre Patte and George Saunders considered the propagation of sound in architectural spaces using geometry. Antonio Gaudi, a nineteenth century architect from Catalonia, used a geometric modeling system called "graphic statics" in order to simulate the structural loads on his designs. In one way or another, designers have

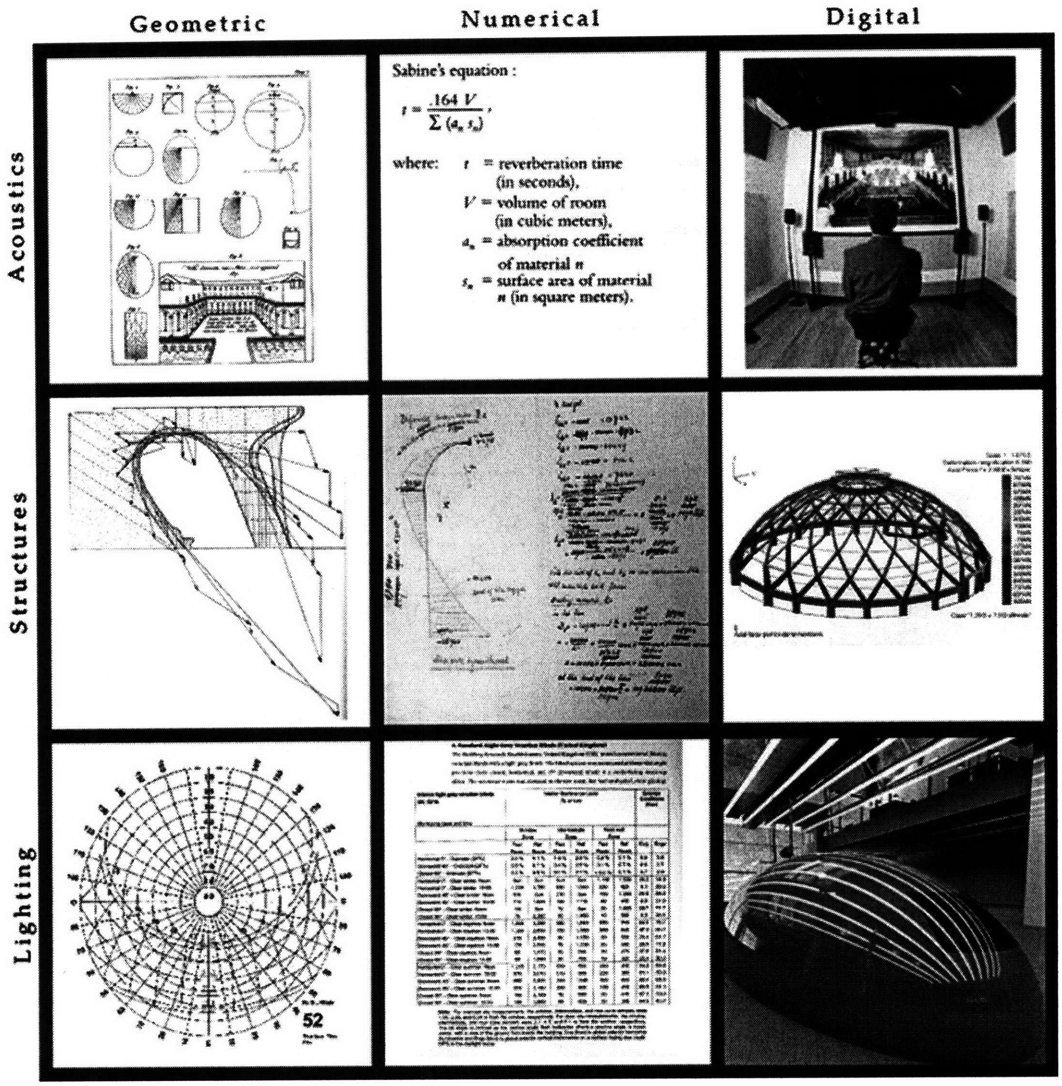

Figure 2. Simulations: (top left to bottom right) sound reflections, Sabine formula, sound lab, graphics statics, load calculations, load visualization, sun chart, lighting table, rendering. Image by the author.

always needed to simulate designs before they were built.

Previous cultural studies of the use of information technologies in design describe practitioners who are focused on an opposition between traditional and digital simulations.[19] At a time, design practice was framed in terms of this duality: is design better served by traditional means or through information technologies? Increasingly, practitioners are not debating whether or not to use new technologies for simulation, but rather how to use them. By examining new conceptions of design, as well as the technologies that support these conceptions, we can begin to identify what design means in the emerging culture of simulation and grasp more fully the contingent meaning of design across cultures.

Fieldwork at Arup

In this dissertation, I explore the practice of simulation in a series of cases drawn primarily from the project history of Arup, a global and highly technical pioneer in the field of building design. In 1946, Ove Arup (1895-1988) founded the firm as a one-person structural engineering consultancy in London. Today, Arup is a nine thousand person partnership involved in at least nineteen different building disciplines and numerous other areas of design. From their celebrated concrete shell structure at the Opera House in Sydney to their acoustical predictions for the Lincoln Center renovation in New York City (to be unveiled in 2008), Arup has used innovations in simulation to challenge the discourse in building design and articulate new possibilities for the field. These innovations have not only led to new designs, but also to new conceptions of knowledge, form, and identity among designers. My study will account for the role of simulation in the dramatic development of Arup. I will describe how the firm has used simulations to challenge conceptions of design and how this has expanded their domain of practice.

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19 See the ethnographic work of Sherry Turkle and Donald Schön The Athena Project, A report to MIT.

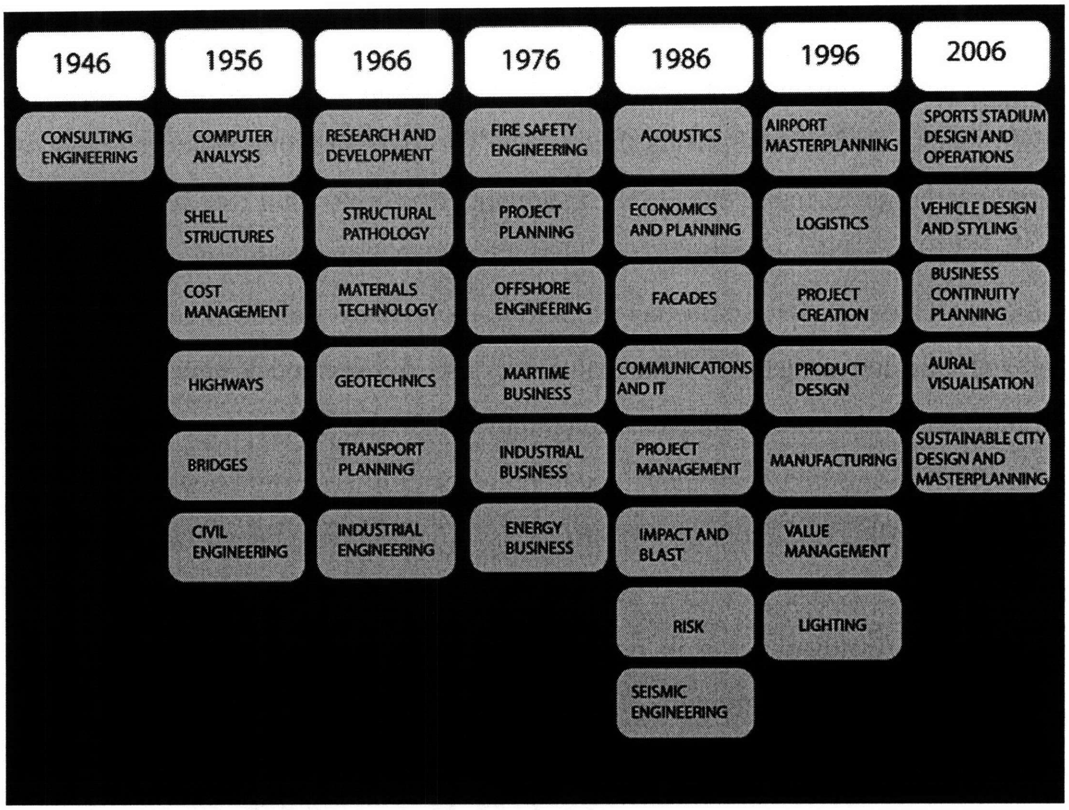

Figure 3. The expansion of disciplines at Arup. Image by the author.

On November 17, 1963, members of Arup, a global design consultancy, met at their central office in London for a "Symposium on the Use of Computers."[20] Although the computer had appeared as a commercial product just a decade earlier, participants at the symposium already saw the computer as a necessary part of their practice.[21] It was introduced as "the electronic brain of popular imagination" and its presence was greeted with both excitement and anxiety.

Early assertions from the symposium about the opportunities and pitfalls that would accompany computing, were recorded in an issue of the Arup

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[20] *Arup Newsletter* 17 (November, 1963)

[21] "Where actual realization is a dominating factor [the computer] is not only a great advantage but it is a necessity." Ibid., 17.

Newsletter.[22] Symposium participants considered a range of ways in which computers might change their practice. Peter Dunican speculated that computers might change the way engineers think. "The very fact that one would be using a computer ought to make one think systematically about what one was doing."[23] Others discussed the possibility that the computer might enable new a range of designs. "The engineer would be free to give more of his time to more interesting and complicated projects."[24] The computer also represented a new freedom of professional exploration. "It may eventually take the odious routines off our hands."[25] The group agreed that the computer would necessitate new roles in the office, to handle computers and in particular, programming, which was described as a "completely new job."[26] Pavl Ahm said "If we did start using computers, special men would develop in our office."[27] At which everyone in attendance laughed, but they understood exactly what he meant. "We needed people with this specialized knowledge to act as a link between us and our problems and the computer."[28] The computer suggested all these possibilities: new ways of knowing, a new range of forms, and new kinds of professionals in design.

Computers evoked many of the deeply held aspirations and fears of engineers. The newsletter made note of this. "There were agitated movements that indicated that the discussion was on the boil."[29] Ove Arup, the founder of the firm, was among the most agitated of the participants. "Design by computer was impossible," he argued.[30] "A computer has to be told what to do." Arup's words

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[22] The Arup Newsletter includes a set of papers presented at the symposium and notes from an anxious discussion which followed. Ibid., 17.
[23] Ibid., 21.
[24] Ibid., 17.
[25] Ibid.
[26] Ibid., 1.
[27] Ibid., 24.
[28] Ibid., 24.
[29] Ibid., 21.
[30] Ove Arup, Ibid., 22.

suggested that the computer should be seen in juxtaposition to the designer. "Design is visual. You can see immediately whether something is sensible or not."[31] To oversee this distinction was to put the designer in jeopardy of being mechanized.[32] Arup dramatized the implications of mechanization by making an analogy between the computerized design office and the workings of an automated farm owned by a friend of his. "Those unfortunate cows that do not conform, those that have too much or too little milk for the machine, have to be got rid of!"[33] Ove Arup's troubled comments highlight the degree to which the symposium was about the affect of computers. Many of the symposium's attendees were fearful that the computer could come to "dominate" their lives.[34] "Why should a computer determine the design?"[35]

Ove Arup and his colleagues had already started to define their work in relation to the perceived capabilities of the computer. Today's computer simulations represent the latest in a series of technologies that practitioners at Arup have used adopted, sometimes reluctantly, as a means of further defining both their professional relationships and their approach to design. They have learned that creating a place within the professional world of design increasingly means negotiating relationships through simulations and with them.

Arup is significant because of the influential, collaborative tradition of their practice. Collaboration and competition are implicitly linked in their work. At the symposium of 1963, the discussion touched upon the implications of computing for professionals relationships between Arup and it's collaborators, particularly architects. For many years, being an engineer at Arup has meant negotiating a professional role in relationship to architects. In his speeches and

[31] Ibid.
[32] Ibid.
[33] Ove Arup, Ibid., 24.
[34] Peter Dunican, Ibid., 24.
[35] G. Wood, Ibid., 24.

writings, Arup frequently juxtaposes the goals of engineers and architects.

> "The reason for the difference between the architectural and engineering 'climate', so to speak, is very complex. It is partly a matter of terminology, partly a matter of historical accident, and the consequent training of architects and engineers, and mostly a matter of what is commonly supposed to be the difference in content or context -- architecture being concerned with producing works of art; engineering with utility structures."[36]

During the twentieth century, building engineering has taken on the role of architecture's other. In *Behind the Post-Modern Facade*, Magali Sarfatti Larson, a sociologist who studies professions, writes:

> "In the face of engineering's more-established position, it was strategically easier for architects to base their professional claims on the aesthetics of construction than on technological mastery or scientific methods. Thus, the image and identity of modern architecture remained centered on the subordination of technology to design."[37]

Some engineers at Arup have embraced their role as technologists. Others see the computer as a threat to their relationships within the firm and their relationships with architects, their primary collaborators. The juxtaposition of architects, engineers and now computers presented a complicated set of professional dynamics for symposium attendees to disentangle. Some attendees

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[36] Ove Arup, *The Arup Journal* 5 (3 September 1970): 2

[37] Magali Sarfatti Larson, Behind the Postmodern Facade: Architectural Change in Late Twentieth-Century America

were already on the defense. Philip Dowson reassured the group that "the computer couldn't really take the act of designing away from the architect... the essential thing to remember was that a computer didn't possess an imagination."[38] Other attendees looked forward to new empowering relationships among the three. R.W. Hobbs, suggested "a computer ought to give the architect more choice, rather than simply produce an optimum solution for him."[39] At this early event in the history of computing at Arup, there were already intimations of a change in the way engineers and architects would negotiate professional boundaries. The computer threatened to change this relationship. To participants in the Symposium, it seemed as if professional dynamics and decisions would develop out of a tension between three, not two players: the engineer, the architect, and the computer.

Through an examination of accounts from practitioners at Arup, I will illustrate how simulations have been crucial in opening up new technical and professional realms of practice. I examine these accounts, not to somehow uncover in an absolute sense how new information technologies for simulation have changed design, but to understand more clearly the ways in which simulations are used in professional claims about what constitutes design, what design does, and who can do it.

Methodology

Attaining empirical evidence of competing conceptions of design is not simple. It is not sufficient to merely observe designers at work. Observation cannot penetrate into the thinking that lies beneath visible behavior. Nor is it

[38] Arup Newsletter 17 (November, 1963): 22.
[39] Ibid., 21.

possible to get at underlying conceptions through standardized questions. Questionnaires run the risk of being too narrow in their terms and framing to capture the full range of design thinking. Although this study cannot be classified as a conventional ethnography, the methodology that I have chosen draws primarily upon traditions of ethnography and qualitative research from anthropology and sociology.[40] I have carefully chosen my studies at Arup, rather than observing daily life at the firm, as a traditional ethnographer might do. I call my research "socio-technical studies" at Arup, because my work combines an examination of how social and technical aspects of design fit together.

My study has drawn evidence from the oral and material culture of Arup, including interviews, observations, simulations, journal articles, technical papers, books, images, and popular media. I spent a year collecting this evidence at Arup offices and archives in Cambridge (MA), Cambridge (UK), New York City, and London. Among the most important resources in my writing have been my field notes from sixty in-depth, unstructured interviews with practitioners at Arup. In these interviews, I tried to uncover conceptions of design that I was not aware of or prepared to interrogate at the start of this study. This method required careful probing, reflection and redirection during the course of each interview. In these interviews, which lasted from one to three hours, my goal was to access personal conceptions of design which were supported by reference to information technologies. I developed lengthy field notes from these interviews, which were then subject to analysis in the context of additional evidence from observation, project documentation, and first-hand experience with simulations. Finally, instead of summarizing the results of my interviews, which would dilute the subtle discourse of practitioners, I have selected salient excerpts that illustrate the

[40] I received my ethnographic training from Professor Sherry Turkle in the Program in Science, Technology, and Society at MIT, Susan Yee in the Department of Architecture at MIT, and in the Department of Anthropology at Harvard University.

competing conceptions of design that I seek to characterize. Because of the unrepeatable nature of this method, its results are subject to serious criticism, against which the only defense is a sensitive interpretation of the evidence and a rigorous account of the context of my work.

In referencing the subjects of my research, I use the terms "practitioners," "professionals," and "designers" somewhat interchangeably. I rely on professional terms like "engineer" and "architect" to make more subtle distinctions between subjects. However, these distinctions are much blurrier in practice than we might expect them to be. In each reference, I try to be as faithfully as possible to the way the subject presented themselves to me.

What is a Simulation?

The term "simulation" has a circuitous history. The Oxford English Dictionary notes that simulation can be traced to the Middle Ages, when it was used to identify a practice or object that imitates for the purpose of deception.[41] However, with the invention of systems engineering and computers in the 1940s, the term was appropriated by the technical world to signify more practical applications, that is, "the technique of imitating the behavior of some situation or process (whether economic, military, mechanical, etc.) by means of a suitably analogous situation or apparatus, esp. for the purpose of study or personnel training."[42] In this sense simulations and simulators are, respectively, the techniques and apparatuses deployed for both the production of knowledge and for the production of new generations of practitioners.

Understanding and discriminating among simulations in the context of

[41] *Oxford English Dictionary* (Oxford : Clarendon Press; New York : Oxford University Press, 1989)
[42] Ibid.

Arup's offices is more complex than it might first seem. Simulations vary widely in their construction, use and meaning. Sometimes simulations are identified in relationship to other kinds of representations. Peter Galison calls simulations "models running in time." Alternatively, simulations are differentiated by practitioners according to the subjects they are used to represent for example lighting, acoustics, or structural forces. A simulation might be an explanatory tool or a tool for exploration. It might suggest new possibilities or help practitioners convey what they already know instinctively. Finally, practitioners differentiate simulations in terms of the interactions it allows or doesn't. A simulation might be a black box, it might be immersive, or it might offer a view from a "god's eye" perspective.

Design practitioners at Arup often cannot agree on how simulation is different from other practices of representation. Does simulation constitute its own realm of practice? Perhaps not, but my analysis of discourse at Arup reveals that the term "simulation" is invoked by design professionals in order to make new conceptual distinctions. These distinctions might be among ways of knowing in design, means of classifying design forms, and avenues towards establishing an identity as a designer.

While we might be hard-pressed to find a static definition of simulation, we can explain simulation as a rhetorical device for making distinctions in practice. For many designers at Arup, simulations represent a conceptual rift between new and old ways of practicing design. For example, some at Arup use simulation in order to draw a boundary between generations, between young practitioners who are accepting of simulations and older practitioners who are more skeptical.

By giving attention to the ways in which design professionals search for the meaning of simulation, I'm treating the term empirically. Geertz explains such a study as interpretive.[43] In *Interpretations of Culture*, Geertz writes "...man is an animal suspended in webs of significance he himself has spun, I take culture to be those webs, and the analysis of it to be therefore not an experimental science in search of law but an interpretive one in search of meaning."[44] The search for the meaning of simulation in design practice has an important professional function. Simulation is a frame through which design professionals reflect on the technical and cultural changes in their work and make new ideological and competitive assertions about what it means to do design and to be a designer.

At Arup, simulations take on diverse forms and are used in many different ways. They are part of a larger category of professional representations that are difficult, and sometimes unnecessary to distinguish. Simulation is often synonymous with other terms, like visualization and model. These representational artifacts all have troubled philosophical pasts.

> Few terms are used in popular and scientific discourse more promiscuously than 'model'. A model is something to be admired and emulated, a pattern, a case in point, a type, a prototype, a specimen, a mock-up, a mathematical description-- almost anything from a naked blonde to a quadratic equation -- and may bear to what it models almost any relation of symbolization.[45]

What is the difference between simulations, models, and other mechanisms of abstraction used by practitioners? Many at Arup explain that they don't have an answer to this question, either because these terms are interchangeable, or because the distinctions are simply not apparent outside of the

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[43] Clifford Geertz, *The Interpretation of Cultures* (Basic Books, 1973).
[44] Ibid.
[45] Nelson Goodman, Languages of Art: An Approach to a Theory of Symbols (Bobbs-Merrill, 1968), 171.

context of use. Does this mean that distinguishing simulations from models, visualizations, and other representations is not important for practice? Not necessarily. The term simulation has a functional significance in context, even though a general meaning for the term cannot be easily extrapolated from these instances of use. I believe, along with philosophers and science and technology, like Sergio Sismondo and Eric Winsburg, that simulations do not have fixed definitions or categorizations, any more than design does.[46]

Simulations are never handled or attributed meaning in isolation. They are part of a broad system of knowledge, composed of theories, material and mathematical artifacts, and interpretations. Philosopher of science, Eric Winsburg, writes about modeling and simulation as occupying an uncertain place between better established areas of scientific practice, like theory and experimentation.

> While models generally incorporate a great deal of the theory or theories with which they are connected, they are usually fashioned by appeal to, by inspiration from, and with the use of material from, an astonishingly large range of sources: empirical data, mechanical models, calculational techniques (from the exact to the outrageously inexact), metaphor, and intuition.[47]

Winsburg shows how models and simulations are assembled from many ways of knowing. He explains that, as semiotic systems made up of symbols and signs, simulations are interpreted and assigned meaning in context. In contrast to Winsburg's studies, Herbert Simon calls for a theory and taxonomy of representation, as an essential component in the development of his new science

[46] See Sergio Sismondo, "Models, Simulations, and their Objects." Science in Context 12 (1999), 247-60. and Eric Winsberg, "Models of Success vs. Success of Models: Reliability without Truth." Synthese 152 (2006), 1-19.
[47] EricWinsberg,"Models of Success vs. Success of Models: Reliability without Truth," 4.

of design.[48] Here, I grapple with the problems inherent in doing so. I believe that we might come closer to an understanding of representations and their implications for design practice by eschewing the search for a comprehensive explanatory theory.

Simulation as a Space of Exchange

The dynamic meaning and function of simulation serves a purpose at Arup. Simulations are often created to meet the specific needs of clients. This is to say that Arup often develops simulations and professional relationships in tandem. Sometimes the two become linked so closely that they are difficult to disentangle. Clients come to expect certain simulations from Arup. According to Peter Bressington, of the Arup Fire Group in London, these professional partners become comfortable with "their" simulations and request or even demand that they be used on every project, even if that project doesn't necessarily merit the use of such simulations.

With the creation of each simulation, practitioners at Arup ask, "what type of relationship will this satisfy and for what end?" The success of any simulation, depends it's fit with an audience. Simulations must be technically defensible but also culturally palatable. On each project and with each new client, Arup must learn how to use simulations to engage audiences on their own terms. One way of acknowledging how simulations enable successful interactions among Arup practitioners and clients, collaborators, and building regulators is to look at these technologies as "trading zones."[49] In Image and Logic, historian Peter Galison

[48] Herbert Simon, *Sciences of the Artificial.*
[49] The term "trading zone" is defined in Peter Galison. *Image and Logic.* I do not mean to suggest that the role of one kind of representation, simulations, can be easily separated from the muddle of communication that happens in trading zones. The trading zones used by design professionals are

introduces the term trading zone in order to explain how pidgin languages are used by to communicate across social and epistemological boundaries. By Galison's account, different social groups can productively "trade" objects and information without having the same understanding of the exchange. He writes about the world of microphysicists. "Simulations constituted what I have been calling a 'trading zone', an arena in which radically different activities could be locally, but not globally coordinated."[50]

Although the concept of a trading zone is not widely used in design discourse, using the metaphor of "a space" to describe a range of possible designs is common. In *Sciences of the Artificial*, Herbert Simon introduces the notion of a "space of alternatives."[51] The use of this spatial metaphor suggests that there are techniques by which designers can "find" good designs, if they look in the right places. Simon's view is a recapitulation of a reoccurring metaphor throughout the modern movement, that design *is* exploration.[52] For example, Frank Lloyd Wright wrote "in the stony bonework of the Earth, ... there sleep forms and styles enough for all ages, for all of Man."[53] For Wright, nature held the space of alternatives. By expanding the discussion of design as exploration to include reference to Galison's "trading zone," we acknowledge that design spaces are collaborative and that we should allow for multiple meanings to adhere.

At Arup, simulations are used as participant-specific communication devices. They open up zones in which design participants can coordinate designs without sharing the same conceptions about these designs. For lack of a more

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complex pidgin languages assembled haphazardly. They include references to many kinds of artifacts and representations. Although we cannot completely disentangle trading zones into some fixed set of constituent representations, when we look at projects which incorporate new kinds of simulations, we can see trading zones open up or shifting in discernable ways.

[50] Peter Galison. *Image and Logic*, 690.

[51] Herbert Simon, *Sciences of the Artificial*, 123.

[52] Terry Knight, Professor of Computation in the Department of Architecture at MIT, has spoken extensively on the subject of this metaphor.

[53] Frank Llyod Wright, *Collected Writings* 1, ed. B.B.Pfeiffer (New York: Rizzoli, 1928), 275.

refined term, I am calling these zones "spaces of exchange" between design participants. This term is meant both literally and figuratively. The space of exchange is the place where design representations are shared. It is also defines the boundaries of what designs are accepted as possible and desirable by participants. The space of exchange is both a trading zone and a space of alternatives. Throughout this dissertation, I will examine how Arup uses simulations to shape different spaces of exchange with clients, collaborators, and regulators and in doing so, how they create professional positions for themselves within design practice.

Related Studies

In recent research, information technologies for simulation have been highlighted by designers as offering solutions to new desires like constructing large-scale complex curved surfaces.54 They are attributed with bringing invisible phenomena, like acoustics and airflow closer to hand.55 However, simulations are also involved in broad changes in what it means to do design and to be a designer. Here, I seek to enrich the instrumental view of simulations by describing the social and cultural functions of simulations. "We are moving towards a culture of simulation," argues sociologist and psychologist Sherry Turkle, "in which people are increasingly comfortable with substituting representations of reality for the real."56 In Life on the Screen, Turkle writes about how socializing, working and playing in virtual worlds affects the way we think about ourselves as well as what it means to be human. Here, I examine how professionals in the domain of

[54] See Sheldon, D. "Digital Surface Representation and the Constructibility of Gehry's Architecture." PhD diss., Massachusetts Institute of Technology, 1997.
[55] See *Advanced Building Simulation* ed.Ali Malkawi and Godfried Augenbroe. (New York : Spon Press, 2003).
[56] Sherry Turkle, *Life on the Screen*, 23.

building design think about what it means to be a designer in a culture of simulation.

In The Reflective Practitioner, design theorist Donald Schön defines design as "a conversation with the materials of the situation."[57] This is true in a deeper sense than Schön suggests. It is true not only of the design process, Schön's interest, but of the conceptualization of design as a domain of work. Design does not simply happen within a noteworthy social and technological context; it cannot be extracted from its context. The meaning of design emerges in a conversation with the materials of the situation. The dynamics of this conversation in contemporary practice cannot be explained without an understanding of simulations.

Concerns with simulation as merely instrumental are predominant among many practitioners. In "Models, Simulations, and Their Objects," Sergio Sismondo, criticizes the limited narrow, functional framework for thinking about simulations widespread among scientists.[58]

> Seeing models and simulations just in a space between theories and data, the typical way of seeing them, misses their articulation with other goals, resources, and constraints. There are resources provided and constraints imposed by the media in which they operate, because they are created with the mathematical and computing tools available. They are created to fit into particular cultures of research: models and simulations have to take particular forms in order to be accepted. And they are created to fit into particular social settings, becoming objective by balancing among

[57] Donald Schön, *The Reflective Practitioner.*
[58] Sergio Sismondo, "Models, Simulations, and their Objects."

sides in debates.[59]

As Sismondo notes, simulations both define and are defined by the professional work of which they are a part. They have profound implications for the production of both knowledge and professional identity. Historian of science, Peter Galison, examines these issues in his study of the relationship between physicists and their instrumentation. In *Image and Logic*, a history of the material culture of microphysics, Galison explains how the development of simulations challenged the professional identity of scientists.

> As they struggled to find a place in the traditional categories of experiment and theory, the simulators both altered and helped define what it meant to be an experimenter or a theorist in the decades following the Second World War.[60]

If we are to understand new forms of professional life in the domain of building design, we must examine building simulations beyond their instrumental value, for how they change the way that professionals define their practices and seek out professional legitimacy.

On the other hand, we should be wary of seeing simulations as deterministic. In "The Question Concerning Technology," Heidegger warns of the dangers of taking technologies at their instrumental, face value.[61] For Heidegger, new technologies herald new ways of revealing the world. Revealing is at the root of technology's apparent instrumentality. The insights that we gain through technology are practical, a means to an end. As an example, Heidegger asks us to

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[59] Ibid., 254.
[60] Galison, Peter. Image and Logic.
[61] Martin Heidegger, The Question Concerning Technology, and Other Essays (New York: Harper & Row, 1977).

think of a tract of land, challenged in the hauling out of coal and ore. Here, the earth reveals itself as a coal-mining district and the soil as a mineral deposit. The field that the peasant formerly cultivated and set in order appears different through the framing of technology. Heidegger explains that the world is revealed to us through the frames of technology. He cautions that the means of revealing in new technologies can be overshadow and obscure other "essential" human ways of representing nature.

Although the illusion of instrumentality is of concern, many contemporary writers hold that the relationship between new technologies and new ways of seeing are more complex than portrayed by Heidegger. Technologies can reveal different things for different people. Sherry Turkle and Seymour Papert write that computers can create new pluralisms, in which "different people make computers their own in their own way."[62] With simulations at hand and in mind, designers are defining a variety of new practices and embracing a range of new conceptions about design. When we look at simulations, we should resist the temptation to see them as deterministic, an extension of Max Weber's "iron cage." The diversity of new practices in design suggests that simulations enable, not fewer, but more ways of seeing design.

Context of Work

In 2004 and 2005, I participated in an interdisciplinary research project to examine the role of information technologies for simulation in professional change within four domains: architecture, nuclear weapons design, life science, and aviation. This project was initiated in the Program on Science, Technology

[62] Sherry Turkle and Seymour Papert, "Epistemological Pluralism and the Revaluation of the Concrete."

and Society at MIT and funded by the National Science Foundation. Entitled *Information Technologies and Professional Identity: A Comparative Study of Virtuality,* this study revealed that across all four fields, simulations are transforming professional experience, the means by which professionals develop intuition and expertise. "We make our technology and our technology makes and shapes us. New tools enable new ways of knowing."[63] My dissertation extends this foundational work and deepens it. Here, I focus exclusively on one discipline, design, and one site of practice, Arup.

The most obvious audiences for this work are the designers, like those at Arup, for whom the struggle to understand the pragmatic and theoretical implications of their work is an everyday struggle. Further afield, social scientists may be interested in changing notions of design as an important dimension of human behavior. Finally, there is a broad audience concerned with the prominence of information technologies in our lives. This audience strives to understand how information technologies might be implicated in widespread cultural changes.

Outline of Chapters

This dissertation is organized in five chapters. After the introduction, there are three chapters which introduce new evidence into the discourse on how design practice is changing along with information technologies for simulation. Chapter one is an examination of new conceptions of knowledge among practitioners at Arup. Chapter two addresses novel conceptions of form at the firm. Chapter three addresses the implications of these technologies for conceptions of professional

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[63] Turkle, S. et. al. Information Technologies and Professional Identity: A Comparitive Study of the Effects of Virtuality. Report to the National Science Foundation. MIT, 2005.

identity at Arup. Chapter four offers two interpretive frameworks for reflecting on how simulations are used at Arup: simulation as narrative and simulation as theatre. Finally, the conclusion revisits the most salient cases and themes of the dissertation.

CHAPTER 1 CONCEPTIONS OF KNOWLEDGE AT ARUP

During the 1980s, building regulators in London began to express concern about fire safety in large, enclosed public spaces. Vast indoor spaces were becoming prevalent in an increasing number of building types: shopping centers, airport terminals, office atriums.[64] However, existing regulations constrained the floor area in these buildings. "In general, the codes set a limit of 45m travel distance to the nearest exit. When the floor layout is not known they set a limit of 30m distance drawn on plan to the nearest exit." wrote Margaret Law, founder of the Arup Fire Group, in a paper entitled "Fire Protection in Terminal Buildings."[65] Large closed public spaces represented a new typology for building regulators in London, who could not judge how smoke, fire, and people might move and interact in such circumstances. Llyods of London, an office tower in central London, designed by the architectural office of Richard Rogers Partnership, proposed an unusual multi-story atrium, open at each floor. Arup was hired to consult Rogers and the Llyods building became among the first projects in which Arup struggled with regulators over the issue of fire safety in large enclosed public spaces.

Arup often educates clients, collaborators, and regulators in the prescriptive knowledge of local building regulations around the world and helps them conform to these standards. Practitioners like Peter Bressington and

[64] Although train stations have similarly large halls, notes Law, they are usually so lofty and open that smoke does not present a problem.

[65] Margaret Law, "Fire Protection in Terminal Buildings" in *Building Services For Airports* (London: The Chartered Institution of Building Services Engineers, 1985).

Margaret Law, in the Arup Fire Group have themselves helped to establish such regulations in Europe, America, and Asia. However, in the face of an increasingly diversified field of practice, the limitations of prescriptive knowledge have become apparent. Today, Arup is proposing alternative ways of knowing through simulation to alleviate the concerns of building regulators in cases where the prescriptive knowledge of local building regulations pose unacceptable limitations on design.

For the Llyods building, Arup was able to obtain a relaxation from London regulators by proposing smoke flow simulations as a means of explaining and jointly examining the safety of the atrium space. Richard Waters, a physicist working at Arup, used computational fluid dynamics, typically used for airflow analysis, to calculate smoke flows in the Llyods atrium. But the computational fluid dynamics calculations produced little more than numbers. "One of the problems is actually illustrating the results of the calculations," says Law.[66] For building regulators concerned about Lloyds' atrium, Law presented the results of calculations as two-dimensional flows in a sectional drawing of the building. Law used this drawing as a crude simulation, a space of exchange with regulators. The drawing became a proxy for the building, through which Arup's practitioners, Roger's architects and London's regulators could share and jointly discuss the safety of the building before it was completed in 1986.

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[66] Margaret Law, interview by the author, 2007.

Figure 4 The Llyods of London Atrium. Image courtesy of Arup.

In their work on another project, Stansted Airport, a vast terminal just outside of London completed in 1991, Arup continued and revised this approach to building regulations. They created a more sophisticated simulation. Stansted was designed by architects at Foster and Partners to maximize flexibility. Inside the terminal, the architects proposed small shops, like stalls open to the larger space. "Existing terminals were often a series of small rooms; Stansted on the other hand, was to be one vast room."[67] According to Law, the idea was to encourage passengers to drift in and out of the shops. However, the lack of compartmentalization worried regulators. The building regulations still called for an exit every 30m. Stansted's roof covers approximately 200 square meters. Standing in the middle of the terminal space, a passenger would be 50m from the nearest exit.[68]

> When the code was written, they hadn't thought of this type of building. You tend to legislate on what you know about. You can't legislate something you [don't] know. Nobody ever thought you were going to put a great big roof over a whole high street of shops.[69]

[67] Kenneth Powell, *Stansted. Norman Foster and the Architecture of Flight* (London: Fourth Estate Wordsearch: 1992), 31.
[68] Ibid., 41.
[69] Margaret Law, interview by the author, 2007

Figure 5 Stansted Airport Terminal. Image courtesy of Foster and Partners.

Arup engineers and scientists, led by Law, constructed an animation demonstrating how people and smoke might behave within the controversial open floor plan at Stansted. "This involved our collecting a range of data from experiments, surveys, and fire statistics, to illustrate how various measures could compensate for a lack of compartmentation," wrote Law.[70] Richard Waters did the computational fluid dynamics calculations once again. The calculations showed that smoke would take 12 minutes to descend to head height in several different circumstances. Law's team combined his calculations with empirical data from observations at existing terminals. "We measured walking speeds of people in the baggage reclaim area, which we thought was reasonably conservative because they would be carrying their baggage."[71] Law then turned to the emerging field of computer graphics animation to represent Water's calculations. "I had seen

[70] Margaret Law, "Fire Protection in Terminal Buildings."
[71] Margaret Law, interview by the author, 2007.

computer graphics of structures, which looked like photographs of structure. They were drawings, but computer generated. They looked absolutely fantastic so I got in touch with them and said, look we are trying to show what it would look like if you were here and had to get out of the building."[72] As in the case of the Llyod's diagram, the Stansted animation represented a shared space of exchange for Arup, Foster and Partners, and building regulators. Although the animation seems crude by today's standards, it conforms to what we expect of a contemporary simulation. It was an on-screen, animated visualization of the building, no mere diagram. It represented a step forward in describing human experience in buildings through simulation. Building regulators readily accepted it as a proxy for the real experience of the building. They were reassured that passengers could escape from the terminal even though it spanned a distance much greater than 60m.

[72] Ibid.

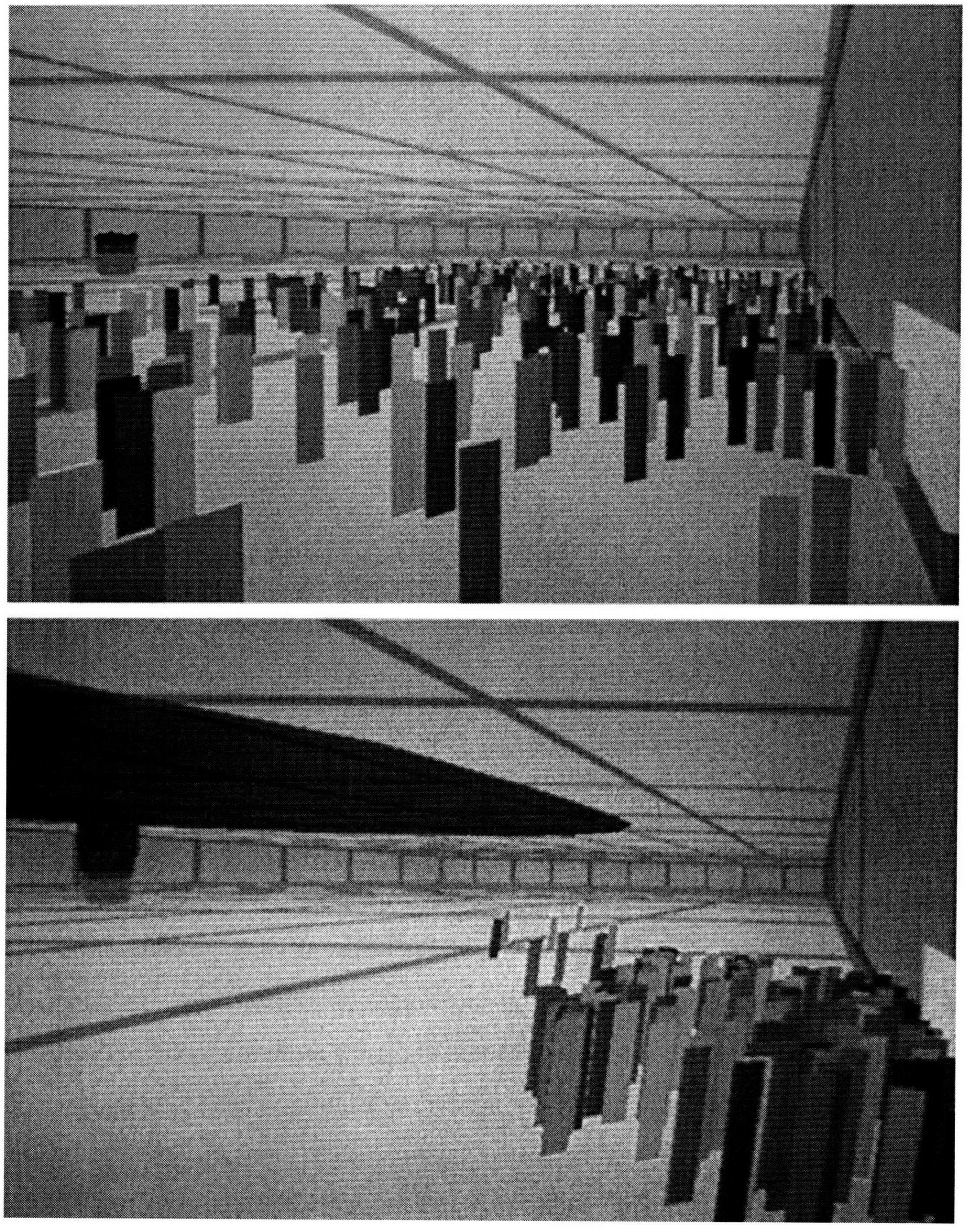

Figure 6. Stansted computer animation depicting abstract people escaping from a cloud of smoke Image courtesy of Arup.

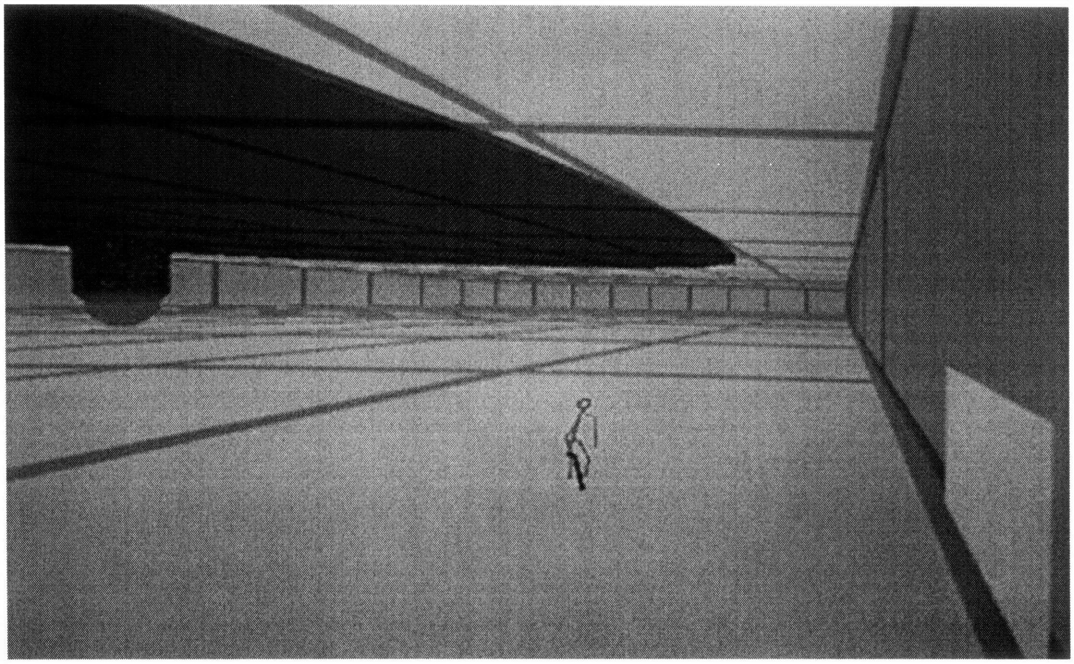

Figure 7. Stansted computer animation depicting the last evacuee. Image courtesy of Arup.

The simulations that Arup used on both Llyods and Stansted were part of what Peter Bressington, director of Arup's fire safety group in London, calls a "bargaining area" between practitioners at Arup and building regulators.[73] When the Arup Fire Group issues a report to the local regulators, it rarely goes through without an intensive period of questioning. Regulators usually ask the Arup Fire Group to follow up on certain questions or present alternatives and variations. Simulations often become the focus for this iterative process. "It is important that you try to explain your results. Pictures and diagrams are important," says Law.[74] Stansted and Llyods are innovations in communication. These simulations put new knowledge in context with what regulators already knew. Arup's work on these project required moving backwards and forwards between the propositions of the architects to the needs of building regulators. These projects illustrate how simulations bridge between and help to reconcile disparate ways of knowing. In

[73] Peter Bressington, interview by the author, 2007.
[74] Margaret Law, interview by the author, 2007.

creating a good simulation, Law offers this advice: "you relate it to what they know and are happy with." [75]

Simulations are not always readily accepted by building regulators as a medium of exchange. In particular, Arup has had problems vetting their simulations in Germany and China. They are still learning how to tailor their simulations for authorities in those countries. In order to create a role for themselves in a global culture of design, Arup must learn to adapt simulations to suit a diverse range of audiences.

One of my findings is that new forms, new ways of knowing, and new identities must compete for a place within the culture of design. In Margaret Law's account, we see a controversial new form for public gathering spaces, a challenge to the prescriptive knowledge of building regulations, and a new kind of design professional, the fire safety engineer. Such changes often go hand in hand. But in this chapter, I will concentrate on how Arup practitioners use simulations to create a place for new ways of knowing in design. In particular I will examine what Bressington calls performance-based knowledge.

Behind the use of simulations on Llyods and Stansted is a conceptual differentiation between two ways of knowing in design: experiencing a design through simulation and scrutinizing a design to make sure it follows building regulations. In the early seventies, Law began to question standardized approaches to fire protection. Applying fire resistant paint and sprinkler systems to an a priori structural scheme is inefficient. Why separate fire safety considerations from structural design? Law worked for years at the London Fire Station, developing fire safety regulations herself, based on experiments and simple mathematical models. It wasn't until after she was hired by Arup and began to work on actual building projects like Stansted Airport that she realized a

[75] Ibid.

limitation in these regulations. Today, fire safety is still widely enforced by building regulations. Margaret Law is now retired from Arup, but the Arup Fire Group has made her mission to challenge building regulations into a business.[76] Peter Bressington identifies building regulations at an outmoded way of knowing for designers. They represent what Bressington calls a "prescriptive" approach to design. In contrast, he champions a "performance-based" approach, a more contingent conception of knowledge in design.

Bressington's distinction between prescriptive and performance-based ways of knowing in design is symptomatic of an effort by practitioners across Arup to situate new knowledge amongst traditional ways of knowing. "You move backwards and forwards from what they know, from regulations, to what you are proposing."[77] The Arup Fire Group is often in the business of negotiating or "finding alternatives to achieve the intent" of building regulations.[78] In this context, it makes sense for Bressington to position Arup's approach to knowledge in contrast to the approach of building regulators. Arup Fire's simulations are designed to bridge between these two epistemological cultures.[79] Designers are using simulation not only to rethink what constitutes knowledge in the domain of design, but how new knowledge enables new professional relationships.

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[76] For instance, Law's approach was used by Arup Fire to reduce costs for Columbia University a fortune in fire resistant paint on the Learner Student Center, a glass and steel building designed by the then dean of Columbia's Architecture Department, Bernard Tschumi. By regulation, all the exposed steel should have been painted to retard the effect of a fire on the structural integrity of building. Arup's simulations convinced building regulators and the fire brigade in New York that in the case of the Learner center, the intent of these regulations could be met through alternative means, primarily through redundancy in the structure. The Arup fire safety group in London used simulations to illustrate the specific, contingent experience of a speculative fire the Learner Center. The performance-based knowledge of their simulations substituted for prescriptive notions about how buildings in New York City should be built.

[77] Margaret Law, interview by the author, 2007.

[78] Chris Marrion, from written correspondence with the author, 2008.

[79] Epistemological cultures are defined in Evelyn Fox Keller, *Making Sense of Life* (Cambridge: Harvard University Press, 2003).

Ways of Knowing

In design, many different ways of knowing are in play. The difficultly of defining the failure of structures in fire is illustrative of this. If we are to understand new ways of knowing in design, available through simulations, we must examine the context in which simulations are put to work.

> To say that the definition of failure of structures in fire is 'complex' is a huge understatement. It is much more than that, beginning right from the most elementary issue of 'what kind of failure' is it that one is trying to define. As the fire safety of a structure is of interest not only to the architect and structural engineer but also to fire safety engineers and regulators/building control officers (not to mention the owner/client). It is the highly varying perspectives of this group of people that confuses the issue and makes it very difficult for a consensus on the definition of failure to emerge, if it were indeed possible.[80]

I rely on a sociological model of knowledge in order to make sense of knowledge practices at Arup. In *Knowledge and Social Imagery*, David Bloor explains the sociologist's approach to knowledge.[81] "Instead of defining it as true belief -- or perhaps as justified true belief -- knowledge for the sociologist is whatever people take to be knowledge. It consists of those beliefs which people confidently hold to and live by."[82] Bloor notes that the sociological perspective is particularly concerned with knowledge that is institutionalized or granted

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[80] Usmani, A. and Rotter, M., Intranet Posting entitled "Failure of Structures Under Fire." Arup Intranet, 2007.
[81] David Bloor, *Knowledge and Social Imagery* (Chicago: University of Chicago Press, 1991), 5.
[82] Ibid.

authority by a social group. The above statement from the Arup Fire Group suggests that there are many social groups involved in design at Arup and they each have different definitions of failure. What constitutes knowledge in design is not easily agreed upon.

The sociological approach to knowledge that I have adopted does not hastily distinguish between true and false knowledge. Knowledge is what people take it to be. The structural engineers will want to know the circumstances under which the structure will no longer be able to support the dead and live loads of the building. The fire safety engineers will consider failure to have occurred when there is a breach of compartmentation and an uncontrolled spread of the fire. The owners may know failure to be a substantial economic loss incurred by the fire, including the costs of repairs and losses in productivity and business. In the practice of design, all these perspectives are in play. Many ways of knowing co-exist and compete for a place in design.

Practitioners at Arup use simulation to create professional relationships around new design knowledge. I will look specifically at how Arup creates relationships around what Bressington calls performance-based knowledge. I will examine how this knowledge is produced in the context of design projects through the use of many simulations in conjunction. I will also examine how performance-based knowledge stands up against other, more personal ways of knowing.

Prescription and Performance

"If you get the science right, then you can get the engineering right."[83] This was the perspective of Dave Rasbash and Philip Thomas, two prominent engineers and fire researchers working at a government research center called the

[83] Margaret Law, interview by the author, 2007.

Fire Research Station in Bosehamwood, England established in the early fifties. The model of knowledge at the Fire Research Station was that universal rules of fire safety can be discovered and codified; prescriptive rules can make buildings safe.

This is the epistemological context in which Margaret Law was trained as a fire safety engineer. Law studied physics and math at the University of London. Until recently, fire safety engineering was not taught in universities. In 1952, she began work at the Fire Research Station. Her early work at the Research Station provides an obvious example through which to study prescriptive knowledge. Prescriptive knowledge is contained in rules, axioms, and facts like our ubiquitous systems of building regulations. This knowledge is derived from precedent or experiment. At the station, most of the work consisted of performing fire resistance experiments and tests on elements of structure. These experiments became the basis for prescriptive building regulations which were used all over London.

After World War 2, new materials and new building types presented a set of new problems. Lightweight curtain wall cladding with no fire resistance started to be used widely in the UK. Building regulators were worried about the ability of these new facades to keep heat from radiating across streets and spaces between buildings in the event of a fire. At the time, regulations did not prescribe the size of windows and no one had a good idea about how fire behaved in enclosed spaces and how it might radiate out from lightweight curtain wall facades. One of the important questions became: what is a reasonable distance between two buildings, if one has a lightweight curtain wall?

Law was set to the task of addressing the curtain wall safety problem. She began to collect information on what kinds of fires could be expected in buildings. A domestic building, for example, wasn't likely to have much combustible material. The ratio of combustible material to floor area was expected to be quite low. These assumptions were built into the existing fire regulations. Law looked at these ratios and was able to determine the intensity of radiation in a typical space. At the same time, there was a lot of work being done on radiation and fire spreading, because of the imposing threat of Nuclear War. Therefore, Law had information on ignition of materials by radiation. Using this available information, Law was able to produce two tables which became the basis for new regulations on lightweight curtain wall facades. [84] Unfortunately, legal restrictions prevented the regulations from specifying the distance between buildings, only the distance from the property line. So the regulation was set at half the minimum distance. This example illustrates how prescriptive regulations were developed at the Fire Research Station. We can see that the result is a universal rule for the distance between buildings, based on a lot of assumptions about both construction practices and buildings in use.

The gap between universal rules and specific design problems meant that in addition to developing regulations, Law and her colleagues had to answer numerous "what if" questions from designers. Law and her colleagues at the Fire Research Station tried to look at fire safety from first principles and develop models to describe how buildings would behave in fires. Although Law says that the Station always had answers to the what if questions because they could refer to their underlying models, the practice was exhausting. Law happened to be quite good at it though. She liked solving real problems. Her favorite part was figuring out the best way to deliver the answer. Delivering the answer was a complex translation. The universal rules developed by the Fire Research Station had to be adjusted for the specific design conditions and for the understanding of client. For instance, architects always wanted to see the solution presented visually. Eventually, handling all the what-if questions became overwhelming. Answering

[84] Regulations are maintained by each local authority. Mostly it is the ministry of housing, staffed by surveyors and others, which maintains these.

these questions and solving for various scenarios became one of Law's main tasks. Law starting publishing on the subject of designing for fire safety in an effort to extend universal rules and make them more approachable by designers. But her publications could not answer every contingency. Bressington's concept of performance knowledge developed out of Law's work to answer these "what if" questions. The problem with the tests done at the Fire Research Station and the problem with the regulations that were developed based on these tests is that they assume simplistic conditions. "In a fire everything is transient" says Law.[85] Experience in buildings is occurs in specific conditions. Knowledge of experience will inherently be partial and contingent. Bressington explains the contingency of knowledge about what people experience in building fires. "Technically," says Bressington, "a fire is a fire. But there are differences."[86] For instance, the flow of people is different in the London and in Hong Kong. In Hong Kong people are not as concerned with personal space, so more people might pass through a doorway at the same time. This leads to different patterns of flow. Performance, as the term might suggests, is not a material measure of a building. Performance depends on the context and the perspective of the audience.

The terms prescription and performance are not universally used or liked at Arup. Margaret Law explains that she rarely uses them.[87] Mikkel Kragh, a forty-something member of the Environmental Physics group at Arup, doesn't care for the term, performance. "I'm not sure that I like the term. It sounds very academic."[88] However, Kragh uses the term with architects, because it part of a language about knowledge that they recognize. "We are moving towards predicting performance," explains Kragh.[89] For Arup, this means new

[85] Margaret Law, interview by the author, 2007.
[86] Peter Bressington, interview by the author, 2007.
[87] Margaret Law, interview by the author, 2007.
[88] Mikkel Kragh, interview by the author, 2007.
[89] Ibid.

relationships with collaborating architects and building regulators. Kragh explains it as having more choices. "We can choose to comply with codes or to bypass them through simulations."[90]

Prescriptive and performance-based knowledge are not mutually exclusive. The risks and reliability of each approach are weighed carefully in each project. This is because when juxtaposed to the tested knowledge in regulations, performance can suggest increased risk. "This move is contractually scary," says Kragh.[91] The project managers are concerned about taking on more liability. Arup adjusts their use of simulations to accommodate these fears. For instance, explains Kragh, performance simulations may be used in the proof of concept but not for legally binding verification. Design decisions at Arup are always based on multiple ways of knowing. The remainder of this chapter will explore how simulations fit in among other ways of knowing used by Arup as well as clients, collaborators, and regulators.

Veracity and Validity

Practitioners at Arup use simulations to exchange knowledge with many types of professional partners: architects, developers, and building regulators to name a few. In each of these interactions, Arup practitioners separate questions about the basic veridicality of simulations from questions about their validity. Veracity is a matter of science; validity is a matter of cultural palatability.[92] Simulations may be valid if they conform to the assumptions and expectations of audiences, but if they are based on false premises, false science, then they will

[90] Ibid.
[91] Ibid.
[92] This distinction is explained more fully in Nelson Goodman, *Ways of Worldmaking* (Nelson Goodman: 1978), 125-129.

undoubtedly be false. Simulations must do both. Although they are never true in an absolute sense because they are abstractions, simulations must conform to both the needs of audiences and the laws of science.

Fire safety algorithms and software are only one of many premises upon which the Arup Fire Group assesses buildings and they are typically not developed in-house. Chris Marrion, an American engineer in the Fire Group of Arup's New York office, calls the knowledge about fire safety that he brings to clients and collaborators "common sense."[93] Marrion's expertise is in determining how the science of fire safety can be applied on different projects with different clients, collaborators, and regulators. Debates about the validity of simulations in the Fire Group typically concern input assumptions. These assumptions are the common sense notions which Marrion uses to bridge between the science and the particular needs of his projects.[94]

Many assumptions go into a simulation.[95] Some of these assumptions, like the physical properties of a building, are explicit variables in software. For instance, members of the Fire Group often debate and tinker with the variables that represent the different types of flammable materials in a given building. These variables and whether they are likely to change are issues used to predict the dynamics of fires.

In the hypothetical case of a museum, the contents of the building could be expected to change with each exhibition. For instance, a show featuring small paintings behind glass and a show featuring large wooden sculptures pose

[93] Chris Marrion, interview by the author, 2007.

[94] Chris Marrion, interview by the author, 2007.

[95] Some of these assumptions are standardized. In the case of energy modeling, Ashrae is an example of standards which aide designers in calibrating their simulations by prescribing inputs and acceptable outputs. However, standards are constantly being revised and figures like those offered by Ashrae are considered too conservative or outdated by practitioners like Mikkel Kragh. Also abstraction or skeletonization requires assumptions about the nature of these variables. The variables may be substitutes for a more complex description in which the relationship between the more complex description and the abstraction requires theory or extensive observation.

different risks. In the rail industry, there are equally difficult problems of determining what inputs to use. Rail vehicles vary immensely in size, materials, fuel, and trigger points. Arup engineers must rely on available information and their own experience to make assumptions about these input variables.

Other assumptions are less explicit. Traditionally, assumptions about the behavior and experience of humans living and working in buildings which are standardized or integrated into regulations often go unchallenged. Perhaps these assumptions have remained less explicit because practitioners lack the language to describe them rigorously. This situation is changing. In an increasing number of fields, like fire safety and energy modeling, practitioners are considering assumptions about human experience as something that might be interrogated through simulations.

Chris Twinn, a middle-aged architect and engineer working on energy issues at Arup's London office, sums up the uncertainties of human behavior in buildings as "the question of human interface."[96] Twinn leads a sustainability initiative at Arup's London office. As such, he is concerned with the assumptions about human behavior built into our representations of energy use in buildings. He is concerned with seemingly simple issues, like how the inhabitants of buildings operate its windows and doors. Inhabitants may draw the shades, for example, when it's too sunny. That's fine, as long as they don't turn on the lights when the room then seems too dark. They should reopening the shades, at least marginally. When practitioners run lighting and energy simulations they often assume that people act "rationally," that they don't commit such energy use errors. Energy performance will be off if the blinds are left down and practitioners assume they are up. Typical simulations may also overlook extra appliances like space heaters and fans that people bring into buildings to change their

[96] Chris Twinn, interview by the author, 2007.

environment. Finally, Twinn explains that there are assumptions about basic human comfort that need to be challenged. Comfort is difficult to assess, asserts Twinn. For one thing, there are different comfort levels for different people and for different activities. People are willing to sit in the sun if they are eating or reading a book, but not if they are working on a computer, when glare can be a factor. A considerable amount of Twinn's time is spent thinking about humans not building systems. "One of the hardest things to do is predict the energy use in buildings," says Twinn.[97] The tools for assessing both human perceptions and responses are not there yet. "Car companies don't try to estimate the amount of fuel you'll use per year."[98] One approach to tackling assumptions about human comfort, says Twinn, is to look at the problem as "alleviating discomfort."[99] This assumes that discomfort is easier to track.

Twinn speculates that other disciplines may find it easier to account for human behavior. "In fire safety the decisions are black and white. You can make a list of rules for behavior in a fire. It's simple enough. Will people turn right or will they turn left? At what point will they react to a fire alarm?"[100] However, practitioners in the Arup Fire Group do not see the human interface problem as being as trivial in fire safety. On the contrary, Peter Bressington says that the most recent controversies in his group have been over technologies for modeling evacuation, the behavior of people in a fire. Despite their early successes on the Llyods of London and Stansted Airport projects, Arup fire safety engineers remain skeptical about the veracity of the underlying premises in their simulations. "You can't get it spot on with these models. I'm still not convinced that these models are worth the investment. It is easier to model smoke from a fire

[97] Ibid.
[98] Ibid.
[99] Ibid.
[100] Ibid.

than anything to do with people."[101]

Arup practitioners sometimes get around these uncertainties by adapting simulations to satisfy the assumptions and expectations of different audiences. For instance, the simulation produced for a governmental compliance check, with building regulators as the audience, might differ from the simulation produced for a developer, in anticipation of their use of the building and the use of future inhabitants -- a process called future proofing. Governmental compliance checks are often mandatory, but they may not be valid from the point of view of other audiences. In most countries, there is legislation governing whole building performance. Arup has to conduct compliance checks in order to prove that their buildings meet certain widely acknowledged standards. However, these standards only have a relative measure of truth. Arup typically creates multiple simulations; some satisfy local governments, others satisfy their clients.

One of the dangers of simulations is that by varying the assumptions, it can be made to show nearly any result. This is what historian David Mindell means when he says that simulations may be "doomed to succeed."[102] Given the inherent malleability of simulations, how do design professionals reassure themselves, their clients, collaborators, and regulators of the acceptability of a simulation result? The answer is that they don't show just one result. Typically, practitioners at Arup produce a range of results with different assumptions. These iterations form a context of evaluation, which helps to separate questions about

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[101] Peter Bressington, interview by the author, 2007. Bressington has updated his position as follows: "In discussing evacuation simulation - modeling of flow is straightforward and it is possible to model speed and physical attributes. The more challenging issue is modeling human behaviour because of differences between people and the changes over time attributed to experience. For example, before 9/11 it was often difficult to get occupants of a building to move upon hearing a fire alarm, post 9/11 especially in tall buildings this is not so much of an issue. Of course over time it is likely that people will revert to pre 9/11 behaviour." Peter Bressington, e-mail correspondence with the author.

[102] Turkle, S. et. al. *Information Technologies and Professional Identity: A Comparative Study of Virtuality.*

the basic veridicality of a simulation from questions about assumptions and expectations. A meaningful simulation, argues Roger Chang, a young mechanical engineer at the Arup office in New York, is one that involves many iterations over various assumptions and designs. From this set of iterations, practitioners can identify which designs are the "best options" and the "most cost effective" in context.[103]

In order to distinguish between these variations, Arup practitioners also need to establish a baseline measure of building performance. This is a matter of expectations. How should a typical building perform? From Chang's perspective, the results of a simulation can only be judged against a baseline of acceptability. Establishing this baseline is Arup's way of demonstrating the relative improvement of an innovative design over a typical one. Without a baseline, there is no shared understanding of which designs are acceptable or innovative.

Establishing a baseline in fire safety has been particularly difficult. There are often no clear criteria in this area. There are few rules to describe what is acceptable safety risk on a given project. There are no definitive criteria in part because there is a shortage of consistent data about fire and human behavior in fires. Only in the last several years have fire engineers identified the lack of fire safety criteria as a research need.

Discussions at Arup about the uncertainties of inputs and outputs recalls an old aphorism from the culture of computing: garbage in, garbage out. According to Wikipedia, arguably the best reference for computing jargon, the saying "is used primarily to call attention to the fact that computers will unquestioningly process the most nonsensical of input data and produce nonsensical output. It was most popular in the early days of computing, but applies even more today, when powerful computers can spew out mountains of

[103] Roger Chang, interview by the author, 2007.

erroneous information in a short time." [104]

This discourse on "garbage" allows for the algorithm itself, its veracity, to be separated from the validity of input or output. The algorithm becomes a "black box."[105] There is a benefit of separating input and output from processing. A simulation which is a black box is accessible to people who do not have a technical understanding of the underlying algorithms. The black box incorporates a lot of judgments. These judgments do not have to be taken into account on each project, simplifying the problem of creating a simulation. The black box can be questioned of course, and should be. However, discussions about input and output which ignore the inner workings of the black box can be the basis for a non-technical exchange between members of Arup and their clients.

In these discussions, a suspension of disbelief is called for on the part of the clients. They must be willing to assume that the black box works. For some audiences, like insurers, it is important that simulations are not black boxes. "If [insurers] can understand what is happening inside the software, if you can get it to be transparent, then they are more likely to accept it," says Bressington.[106] "Insurers are the most conservative audience. They demand to look at the worst case scenario."[107] In order to avoid creating black boxes, Arup sometimes brings insurers into discussions about simulations early on in the design process. This is a means by which Arup can earn their confidence and let them help guide the project to an acceptable solution. Creating a valid simulation in not just about how the assumptions and expectations of clients are engaged, but also *when* they are engaged.

Practitioners at Arup make a distinction between the veracity of

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[104] Wikipedia. www.wikipedia.com
[105] For more on black boxes see Bruno Latour, *Science in Action:* How to Follow Scientists and Engineers through Society (Cambridge: Harvard University Press, 1987).
[106] Peter Bressington, interview by author, 2007.
[107] Ibid.

simulations, the truth of the premises upon which simulations are based, and the validity of simulations in the context of project-based relationships with clients and regulators. The premises of simulations, the underlying building science and algorithms, are largely developed outside of Arup, in government and academic laboratories. Arup must worry about how to bridge between science and design, how render simulations valid in the eyes of clients.

Chris Marrion describes creating valid simulations as a matter of not only choosing the right tools, but also getting the assumptions and expectations right for each client. Chris Twinn and Peter Bressington explain how new simulations are reopening the debate over assumptions about human experience in buildings. Roger Chang introduces the idea that simulations reveal only relative measures of performance. These perspectives from individuals at Arup suggest that the validity of knowledge produced by simulations is filled with uncertainties. These are uncertainties outside of the black box of technical knowledge programmed into simulations. Of course, there are more uncertainties within this technical realm. But what I have tried to illustrate here are the uncertainties accessible to clients, architects, regulators and other non-technical participants in the design process. Instead of seeing these uncertainties as troubling, as evidence of the unreliability of simulations, we can see them as an opportunity for discussion about ways of knowing in design. Arup uses a performance-based approach to knowledge to encourage such discussions, but also to position their own simulations as the primary subjects and to establish themselves as mediators.

Consensus among Simulations

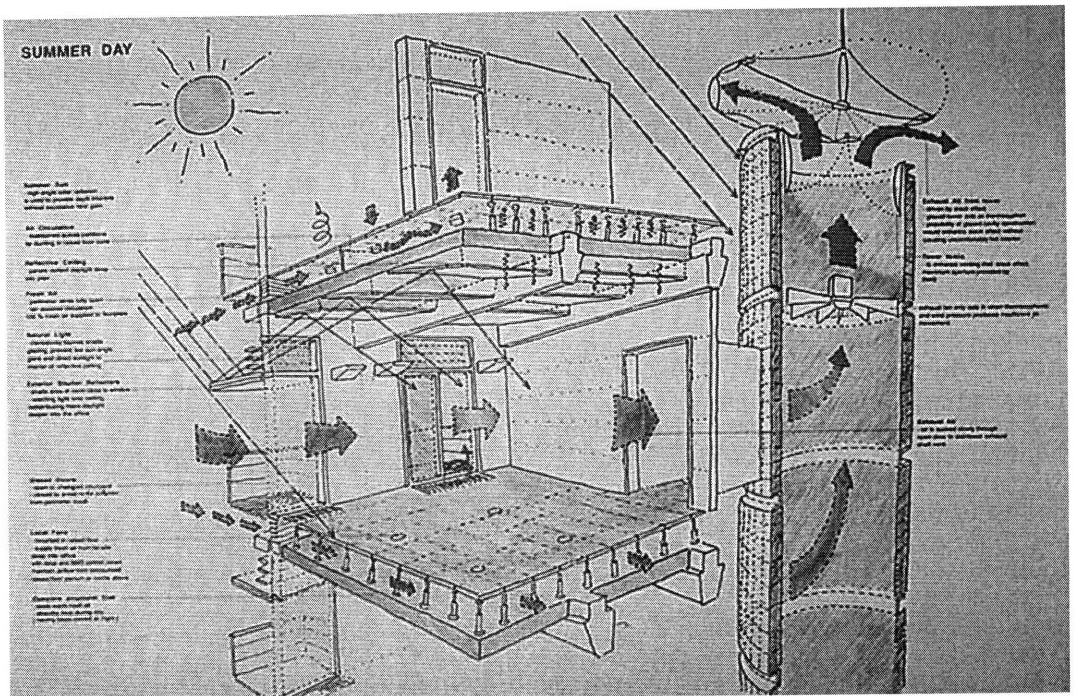
In the last section, I explained how a range of iterations from one simulation are used to give context to individual results. Similarly a range of simulations are used to validate one another. Simulations with different underlying premises can be compared or integrated to form a more holistic picture of a design. Roger Chang, the young mechanical engineer, explains that there is a lack of confidence in any one simulation, a frustration that "the tools aren't good enough."[108] There is also the danger, expressed by Chang, that "people think they know what's going to happen and they correct their simulation accordingly."[109] This error is less likely to go unnoticed when several simulations must be made to correspond. There is still a lot of debate over what constitutes a good simulation and how simulations might be independently validated. Without others measures to back it up, there is little desire among practitioners at Arup to trust one simulation.

For this reason, there are a plethora of simulations in use within Arup's Fire Group. Chris Marrion says that his initial advice to architects is often arrived at through hand calculations, the simplest kind of simulation. Advanced simulations can be time intensive and expensive; they are reserved for later use. In most projects, the Fire Group works their way up to advanced simulations. There are numerous intermediary techniques, for instance, between a hand calculation and an advanced computational fluid dynamics analysis. In between, we can find the use of spreadsheets, akin to automated hand calculations, to handle a diverse array of issues including smoke management, heat, materials, egress, and the placement of smoke detectors and alarms. The fire team also makes use of zone models, which divide a room into heat and smoke zones. Computational fluid dynamics models, introduced at the beginning of this chapter on the Lloyds and Stansted projects, are just one of a host of techniques for simulating fires which are used to inform one another.

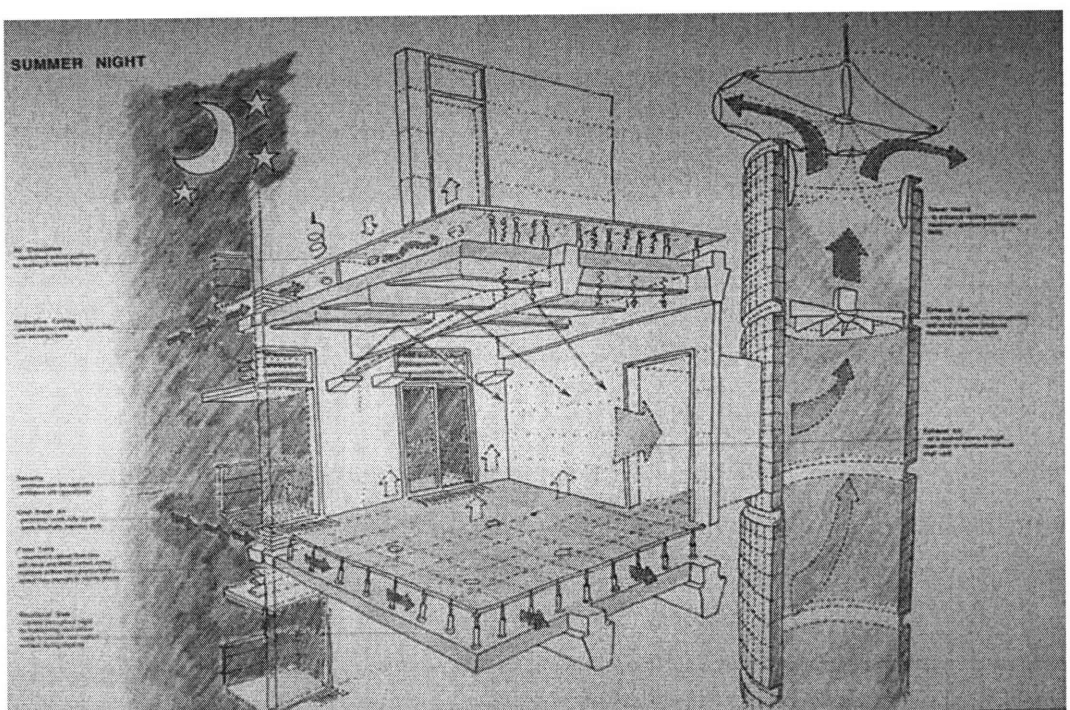
[108] Roger Chang, interview by the author, 2006.
[109] Ibid.

Chris Twinn, the sustainability expert, explains that multiple simulations in different media are often produced in parallel. None of these simulations are completely reliable, but seeing whether they correspond can be useful. One of the early buildings in which Twinn combined many simulations was the Inland Revenue Building, a 40,000 square meter office building completed in 1991 in Nottingham, UK. The architect on the project was Michael Hopkins. During an initial meeting with the architects, Twinn suggested that the building should be designed to eliminate the need for mechanical systems. The mechanical systems were anticipated to push the budget over the limit. As an alternative, Twinn proposed a passive airflow system, a novel suggestion at the time. Twinn and his team suggested tall ventilation towers to draw air through the building using a phenomenon known as the "stack effect." These towers would generate air circulation in the building using differences in air density due to temperature and moisture variations. The client was concerned that air wouldn't ascend the towers with enough speed to generate adequate ventilation. In response, Twinn and his team added fans to the scheme to draw the air up by force and used a set of complimentary simulations to convince the client of the scheme's feasibility. The team used three separate simulation techniques to verify the design. First, finite element analysis was used to simulate the network of heat flows, but not airflow. A second, computational fluid dynamics simulation was used to add airflow analysis. These two computational simulations were combined. Finally, a third simulation, a physical test, was done at Cambridge University. The university used "salt bath testing," a means of representing fluid dynamics by analyzing the dispersion of salt as it is dropped in a vat of water. The resulting plume is videotaped and the video is turned upside down so that the vat resembles a room with ventilation at floor level. This final test gave engineers and clients a counterpoint to the predictions of the two computational simulations. Of course, all of these techniques are simplified representations; all flawed in one way or another. They were found to be fairly consistent though, enough to prove their point. It is important to note that even a physical test, like the salt bath test, is unreliable. There really is no ground for truth in simulation. The best one can hope for is a good correspondence between simulations, generated in a number of ways.

When practitioners at Arup are choosing between multiple possible simulation techniques, it is the particular needs of clients the guide their decisions. There is no sense in which any one simulation technique is objectively more reliable. For example, the client for a transportation center at Dulles Airport asked Arup to design a glass enclosure for an underground train. The client specified that the enclosure should hold up under severe heat -- the heat of a train on fire -- for two minutes. The pre-engineered fire system chosen by Arup was only guaranteed for 20 seconds. Assuming that the glass might break, these dynamics were too difficult to simulate computationally. Arup built a physical model in order to show that the glass could behave to the specifications. Many times, physical tests cannot be pursued in house at Arup because of their expense. This is particularly true in the area of fire safety. Typically Arup fire safety engineers have to make a wish list of physical tests to be done in universities or by government research labs. Occasionally, a physical fire safety test has to be done in-house: when it is the only simulation that meets the client's needs.



Figures 8. The stack effect on a summer day, illustrated in the Inland Revenue Building. Image courtesy of Arup.



Figures 9. The stack effect on a summer night, illustrated in the Inland Revenue Building. Image courtesy of Arup.

Simulations must compete in many different arenas. Arup practitioners weigh their simulations carefully against those of their collaborators and competitors. This is nowhere more apparent than in the area of lighting design. "There are many competing programs for lighting simulation out there right now. None of them have the level of confidence that we have in Radiance," says Steven Walker, a middle-aged lighting designer working in the London offices of Arup. For example, Walker classifies the lighting simulations in 3D Max, a program typically use by architects, as "fake."[110] 3D Max is marketed as an illustration device; it is meant to be an instrument for artists, not a scientific or engineering tool. "It doesn't have the physical accuracy of Radiance," says Walker.[111] "You wouldn't be able to simulate the particular type of lamp."[112] The details of the lamp design and its environment are all highly tunable in Radiance, but less so in 3D Max. Walker argues that in 3D Max, users will have just one virtual light source "like 1000 feet in the air."[113] But the core difference, says Walker, is the way Radiance handles inter-reflections in a process called backward ray-tracing.

My independent understanding of the two programs, Radiance and 3D Max, is that they run on similar backwards ray-tracing algorithms. Obviously, there is a difference between the way that architects and engineers like Walker put their software to use. Engineers are probably more attentive to the various assumptions that go into a lighting simulation, regardless of which software they are using. The culture of use is just as important as the particular software platform. Sociologist Sherry Turkle suggests that people adopt technologies in part because of how those technologies make them feel. Radiance may in fact be more reliable that 3DMax, but its stark interface also just feels more like a

[110] Steven Walker, interview by the author, 2007.
[111] Ibid.
[112] Ibid.
[113] Ibid.

scientific instrument. Radiance's interface is comforting to the culture of use at Arup.

Integrating Simulations

A woman walks through a train station in Firenze. I look on from Arup's London office with Alvise Simondetti, a young Italian architect and researcher in Arup's Foresight, Innovation and Incubation Group. "Look how long it takes us to walk the entire length of the train platform," says Simondetti. That's one surprising thing we never would have known, had we not built this model."[114] The woman is a computer avatar. Simondetti and I are watching her walk through a simulation designed by Arup in conjunction with the British architects at Foster and Partners. In this simulation, you can experience the space of the train station with or without acoustical treatment; you can see the movement of simulated people like the woman, lighting effects, and a visualization of airflow through computational fluid dynamics analysis. There are four physics simulations and one structural simulation at work, says Simondetti. Creating integrated virtual settings like this is part of a project run by Simondetti called "Realtime."[115]

Realtime is an example of an integrated immersive simulation. Here simulations are not put in competition, they are superimposed. Each simulation highlights a different phenomena, in this case human behavior in the space, airflow, lighting, acoustics, and structures. Tristan Simmonds, a young engineer working in the Advanced Geometry Unit, developed this model along with Simondetti. Simmonds wrote much of the software, like the algorithms that map the results of computational fluid dynamics analysis onto a 3D max geometric

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[114] Alvise Simondetti, interview by the author, 2007.
[115] Arup has adopted the Quest3d engine cross-office for this purpose.

model.

The Realtime system is not perfect yet. For example, the computational fluid dynamics map is pixilated. But that is because there are limits to the resolution of such analysis, says Simondetti. There are also still some problems in aligning all the simulations. Realtime uses slightly different geometric models to generate each simulation. For example, the lighting analysis does not line up with the floor plates. Although the mismatch is subtle, one director at Arup easily noticed it during one of Simondetti's presentations.

Simondetti's and Simmonds' Realtime is a context in which many otherwise independent ways of knowing about a building can be woven together into one experience, accessible to engineers, architects, and clients alike. It is one of the strategies at Arup for reducing the rampant problems of specialization. Thirty years ago, Ove Arup wrote, "we are drowning in specialization." Ove Arup championed a holistic approach to design, which he named "total architecture" after the early 20th century manifesto written by Bauhaus director, Walter Gropius.[116] Ove Arup's advocacy for total architecture can be followed up in his papers, speeches, and his business initiatives, like the creation of Arup Associates. Arup Associates is a prototype of an integrated design studio, a merger of architectural and engineering working styles.

Although the firm's aspiration towards total architecture endures, it has continued to grow, diversify, and specialize. Andrew Sedgwick, a middle-aged engineer heading up the Lighting Group in Arup's London office expresses his personal concerns about specialization. "As we specialize… as we produce new organizations… it will be harder to produce holistic design. Who will be the integrator?"[117] Sedgwick sees this as a job for the generalist designer. In America, this has typically been the architect. Simondetti's sees technology, perhaps his

[116] Walter Gropius, *Scope of Total Architecture* (New York: Collier Books, 1962).
[117] Andrew Sedgwick, interview by the author, 2007.

project, Realtime, as the integrator.

Robert Stava, the director of the 3D Visualization Group at Arup's New York office is working with Chris Marrion's Fire Group to create their own integrated simulations using Realtime. Stava is helping the group incorporate simulations of human behavior into their models, not for walking through a space but for escaping it in the case of a fire. This is part of a long term trend, says one young member of Chris's group, to incorporate all manner of simulations into one immersive environment: people, fire, alarms, structures, lighting, etc. The young fire safety engineer believes that despite disciplinary differences, there are enough areas of overlap at Arup to make this integration work. "People often have a mastery over several fields. And where there are gaps, people are forthcoming."[118] Marrion adds that there will always be a delegation of tasks, but most of the engineers at Arup share a core of knowledge that allows them to understand in principle what the other disciplines are doing. However, notes Marrion, the Fire Group's integrated simulation won't be a practical reality for another three to five years.

Despite his concerns about specialization, Sedgwick expresses doubt about the benefits of conflating different types of simulation. He contests the idea, put forward by Simondetti and others, that it is already happening. He sees Simondetti's models as superficial, merely "technical demonstrations."[119] "I'm skeptical about the single model environment," says Sedgwick.[120] He explains that buildings need to be abstracted in different ways depending on what your interest is. Take an integrated lighting and airflow model, for example. The need for particular refinements on each side of this dual integration are not necessarily consistent or complimentary. If a wall has an air supply register which is set back,

[118] Arup Fire Group in New York City, group interview by the author, 2006.
[119] Andrew Sedgwick, interview by the author, 2007.
[120] Ibid.

the dimension of the slot is very important for airflow, but hardly important at all for lighting. Likewise, mullion design is an important detail for lighting, but it may have very little effect on airflow or, to add in another dimension, acoustics. "We are all interested in different things. We work at different times. Integrated simulations are not an enormous design help."[121]

While, Sedgwick expresses doubts about the usefulness of integrated simulations, Peter Bressington supports the idea. He argues that conflicts between models developed by different groups can sometimes be quite healthy. However, he cautions, the approach to these conflicts cannot be "my model is better than your model," but rather "are these models built on the same assumptions? If they are, then there is not issue."[122] Although Bressington expresses optimism about the potential for simulations to be integrated, his words suggests that a consensus among people is necessary for this aim to be met. In other words, integration can be facilitated by technology, but it is inherently social. Integration requires a conscientious attitude on the part of practitioners. Chris Twinn tends to agree with Bressington and elaborates on his point:

> To date, I've not seen the computer being a leading component of integrated design. A database doesn't produce integrated design. Many a designer is just working his layers of the database without

[121] Ibid. Stava notes "I've been part of a concerted effort to integrate varies disciplines models within Arup and several strides have been made since you conducted your research - we can now adapt BIM models such as Catia, Revit, Solidworks, etc into 3ds Max for Visualization, Navisworks is now used as a common destination for most BIM models, Realtime Quest models now work with our Acoustic Teams CATTwalker (Realtime Aocustic software), etc. And the objective of the new Sound Lab under development is to be more of an integrated simulation room. To that end I somewhat
agree with Andy Sedgewick in that I don't see us heading towards a single integrated model but rather a common set of transfer formats that allow us to utilize the same model (or parts of it) in different
software depending on the need." Robert Stava, e-mail correspondence with the author, 2008.
[122] Peter Bressington, interview by the author, 2007.

> concern for other disciplines. There has to be a change in the attitudes of individuals. They have to see the benefit of integrated design.[123]

Twinn studied architectural engineering at the University of Leeds, a program that he says would have prepared him for a professional degree in architecture or engineering. Twinn has not chosen one field or the other. As an employee at both Arup, the engineering foundation of the firm, and Arup Associates, its architectural offshoot, Twinn has tried to integrate the disciplines of architecture and engineering through his work, but also in papers, lectures, and workshops. Since he started at Arup, Twinn has been a champion of integrated design. His current position is group leader of London Building Sustainability and sustainability is increasingly seen as being about collaboration and integration. Twinn has learned that if integrated design is to happen, the impetus must come from people. It is not computers that bring disciplines together, it is people: "how they react and think."[124] Twinn is not alone in his apprehension about the ability of technology to bring people together. Alban Bassuet, a young French acoustician working at the New York office of Arup, says the type of integration suggested by "total architecture" does not come along with simulations as such. "Individuals must create this symbiosis."[125]

Some practitioners at Arup believe that the firm is already doing a reasonable job at integration, but that better technology would help. According to Neil McClelland, head of the Facade Group in Arup's New York office, Arup is on the leading edge because of its ability to "put things together,"[126] He asserts that what Arup can bring to the table, beyond what other specialist consultants

[123] Chris Twinn, interview by the author, 2007.
[124] Chris Twinn, interview by the author, 2007.
[125] Alban Bassuet, interview by the author, 2006.
[126] Neil McClelland, interview by the author, 2006.

bring, is "true integration."[127] This doesn't mean that there aren't acknowledged gaps at Arup, but McClelland asserts that technology may help Arup to bridge those gaps. Right now, however, that technology is missing. There is no central building model. The only common denominator between simulations is geometry, says McClelland.

Arup's consulting business still struggles to resolve the inherent conflict between specialization, further enabled by differences between simulations, and integration, necessary for total architecture. "Arup is still a series of silos," acknowledges McClelland. "The thing is to be aware of the silo next to you."[128] Despite the efforts at Arup to bridge between different disciplines, architects might still be better at integration. McClelland says that Arup's most difficult competitors are architects who do the engineering for themselves and potentially do a better job at design integration. However, some of the most technical designers at Arup see architects losing this ability, "There used to be a master builder, but that no longer is the case," says Mikkel Kragh.[129] As knowledge becomes increasingly performance-based, architects will have more trouble integrated diverse areas of knowledge in design. How can architects evaluate integrated simulations, if each simulation is a black box and the misalignments between them are not easily visible? Are simulations making it more difficult for architects who are not technical to take on the role of the master builder?

In Arup's struggle to make a place for itself among a system of professions and simulations in design, integration is more than the philosophy of total architecture; it is a competitive strategy. Simondetti and Simmonds are is trying to get Realtime running as a lucrative business, a new product which Arup can sell to clients. "I am the salesperson and Tristan is the technical person," explains

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[127] Ibid.
[128] Ibid.
[129] Mikkel Kragh, interview by the author, 2007.

Simondetti.[130] The two practitioners have already won quite a few contracts but have not yet convinced Arup to put in the funds for a one million pound virtual reality setup. "[Realtime] is in a period of incubation," explains Simondetti.[131] This incubation will test the ability of Realtime to make new claims to knowledge in the domain of design. Realtime is a system for knowledge management. It is one of several attempts at Arup, including a Knowledge Management Group led by Tony Sheehan, to define knowledge and to integrate it strategically.[132]

Simulation and Personal Ways of Knowing

Although Mikkel Kragh brands himself as a simulations expert, he can tell a lot from traditional building plans and sections. In most cases, a formal computational fluid dynamics analysis is just a verification of what he already knows from looking at these drawings. Computational fluid dynamics can be used to refine initial guesses, to define how a design diverges from standardized expectations of comfort. However, asserts Kragh, sometimes the technologies can also reveal something completely against one's intuition.

Recently, Kragh published a study about the classic office building in the UK, a structure with abundant glazing and huge internal heat gains from equipment and people. Such offices need an enormous amount of cooling. Certain high performance glazing types portend to improve the thermal performance of offices, reducing the amount of cooling needed. However, this glazing can also

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[130] Alvise Simondetti, interview by the author, 2007.
[131] Ibid.
[132] William Porter notes that there used to be a single integrating simulation: the architect's drawings and specs; all consultant data would be fed into these; a conflict between drawings and specs would typically be resolved in favor of the specs. This left open the authority of the drawings. This problem is what has led to BIM and programs like REVIT instead of the geometrically based AutoCAD and other programs. A variety of simulations can be generated with the data contained in a BIM representation.

trap heat in the building, leading to larger gains. Kragh's simulations have revealed this counter intuitive dynamic. Simulations come into conflict not just with other forms of codified knowledge, like building regulations, but with less explicit ways of knowing, like knowledge through intuition.[133] Kragh asserts that this is one of few cases in which the simulation revealed something unintuitive. Among the most experienced practitioners at Arup, such cases are seen as the exception to the rule.

"You cannot rely on simulations. You have to understand the basis of it, you have to be able to make intuitive judgments," says Alistair Guthrie, a veteran British engineer and a director at Arup who has worked at the firm for almost thirty years.[134] Experienced engineers like Guthrie know that buildings are dynamic and that there is no way to get a truthful static picture of how a building works. Simulations merely give an indication upon which design decisions can be based on. "All modeling is simply confirming one's intuition."[135] Guthrie puts forth this claim, but then softens it. "Although this is not entirely true, we do know what we need it to look like. You don't start with the idea and generate the shape. You start with a shape and the computer conforms."[136] Guthrie's assertions point to long-standing concerns at Arup that simulations, particularly those done

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[133] Differentiating between explicit knowledge and tacit knowledge, like intuition, comes down to the question, "can we simulate it?" The distinction between tacit and explicit knowledge championed by Donald Schön has been incorporated by the Knowledge Management Group at Arup in order to distinguish between knowledge that can be incorporated into computer simulations and the knowledge that resists such representation. Explicit knowledge, sometimes referred to as technical knowledge is assumed to be easily integrated into software simulations. Tony Sheehan, Director of Knowledge Management at Arup, writes, "Technical knowledge can be integrated into processes through calculation plans, standard details or spreadsheets -- a simple example in the corrosion protection field is the translation of a 30-page British Standard into a two-line interactive spreadsheet. This translation allows a less-experienced engineer to benefit from the knowledge of an expert, minimizing the chances for mistakes on a project, and enabling people to reuse templates, sound in the knowledge that they are building on past experience rather than reinventing the wheel." Sheehan, A. and Poole, D., "Making Knowledge Work," *The Arup Journal* (February 2005).

[134] Alistair Guthrie, interview by the author, 2007.

[135] Ibid.

[136] Ibid.

on a computer, may be given too much weight, that they may come to dominate design. The seductive quality of computer simulations is a subject of much consternation among an older generation of practitioners at Arup.

Bob Lang, an experienced structural engineer at Arup's London office, says that there is a dangerous assumption that if you can build it in the computer, then you can build it on site. "You have to develop an intuition about these things before you can use the computer. Young engineers need go out and learn construction techniques."[137] Lang contrasts the contingent, seductive quality of experience gained through simulations with the concrete, pragmatic experience of the construction site. In Lang's era, you had to spend a year as a builder, after graduating from engineering school. Today, new graduates are only expected to spend six weeks on site, says Lang. He believes that young engineers need more hands-on training to understand how pieces go together in construction. All the great engineers, like Nervi and Prouve, understood how forms went together, asserts Lang. Knowledge produced through simulation is supplemental knowledge for Lang. Simulation is not a replacement for experience. Lang's engineering heroes from the past developed experience on the construction site in addition to developing their analytical abilities. For Lang and for many other practitioners at Arup, the two kinds of knowledge, simulation and experience, should support one another.

Conclusions

Simulations are commonly employed in making distinctions between different ways of knowing. Bressington contrasts the prescriptive knowledge of building regulations and the performance-based knowledge of simulations in his

[137] Bob Lang, interview by the author, 2006.

struggle to bypass strict building regulations. Guthrie draws a distinction between intuition and simulation in order to mitigate the perception of risk. Finally, Lang finds the virtual experience of simulation lacking, when he compares it to the concrete experience of the construction site. These distinctions are necessary in order for practitioners to interpret the knowledge produced by simulations. They are part of a discourse which gives context to simulation results and renders them meaningful.

Simulations are used by Arup to define both knowledge and a place for themselves within the system of design. This means that simulation must stand up against other representations of knowledge in design. Arup professionals situate the knowledge that comes through simulation amongst other ways of knowing. In this chapter I have focused on how the performance-based knowledge of simulations is juxtaposed with the prescriptive knowledge in building regulations. Being able to bypass building regulations is an important part of Arup's business. At the heart of this strategy is a new conception about knowledge in design, that experiencing a design through simulation is a more effective measure of its value than scrutinizing a design to make sure it follows the standard practices. Some practitioners interpret this as meaning there is less risk in simulation. "If you can predict, you don't have to take risks anymore; you eliminate risks."[138] The notion that human experiences in buildings can be modeled, evaluated and designed is an important part of this new conception. Building regulations have a limited ability to account for the contingencies of human experience in buildings.

I use the distinction between veracity and validity to understand the contingencies of simulation. The veracity of algorithms concerns their underlying building physics. The validity of the simulations is a matter of context. Simulations are validated in the context of project-dependent assumptions. These

[138] Alistair Guthrie, interview by the author, 2007.

assumptions concern the input and the output of simulations. First, in order to validate the input, simulations are typically produced in multiples. By varying the underlying assumptions, a simulation can be used to produce a range of results. This range of possible results forms a context of evaluation. Second, in order to validate the output, simulations are evaluated in reference to baseline expectations. Simulations are meaningless if there are no clear criteria for interpreting their results. Being explicit about these input and output assumptions separates the question of the basic veracity of the simulation from the means of evaluating alternative outcomes from different assumptions. By separating questions of building science from questions about assumptions (inputs and outputs), practitioners at Arup can create a space of exchange between technical and non-technical design participants. However, this separation can also conceal important questions and should be used carefully.

Accounts from individuals at Arup suggest that the knowledge produced through simulation is filled with uncertainties, about the building itself, the experiences of human inhabitants, and about the receptiveness of different audiences. Instead of seeing these uncertainties as troubling, as evidence of the unreliability of simulations, we can see them as an opportunity for a broader discourse involving experts and non-experts about how buildings should be evaluated.

Simulations are typically evaluated not only against their own assumptions, but against other simulations. These opposing simulations can be in competition or they can support one another. When putting simulations in competition with one another, Arup professionals maintain that no simulation is completely reliable. Conflicts between models developed by different groups can sometimes be quite healthy. But the best one can hope for in simulation is a good correspondence. Sometimes competing simulations come from outside of Arup, from other collaborating firms. The evaluation of one simulation against another is a complex process, which is not only technical, it is also often influenced by social and economic considerations. There is no easy way to ground the validity of any one simulation. Every simulation is a partial perspective on a design, with its own assumptions and weaknesses. Only through the consensus of simulations can an evaluation become legitimate.

Simulations are often juxtaposed in the pursuit of knowledge integration. Overspecialization at Arup is a rampant problem. Who will be the integrator? In America, this has typically been the architect. Many at Arup see it as a job for the generalist engineer or simply as a matter of cooperation between the many specialists. A few practitioners look to software as the integrator. In Arup's struggle to compete in the increasingly specialized world of design, the integration of knowledge through simulations is more than a philosophy; it is a competitive strategy.

Simulations also come into conflict with more personal forms of knowledge like building experience and intuition. When contrasted with more traditional ways of knowing, simulations appear insufficient and unreliable to an older generation of practitioners at Arup. They find the virtual experience of simulation lacking, when compared to the concrete experience of the construction site.

These accounts from Arup illustrate simulations applied in "bargaining areas," as spaces of exchange among engineers of different disciplines and generations, architects, clients, and regulators. In the practice of simulation, building science must be reconciled with project-based assumptions, client expectations, other models, and competing ways of knowing; this is a practice of negotiation. Simulations must co-exist and compete for a place amongst other ways of knowing in design.

CHAPTER 2 CONCEPTIONS OF FORM AT ARUP

"We shape a better world"
- Arup

Shaping Performance

"It was one of those cases where the best architectural form is not the best structural form," [139] remarked Ove Arup, upon seeing Jorn Utzon's winning entry for the design of the Sydney Opera House in New South Wales, Australia. "The sails forming the roof would be difficult to construct because they did not accommodate the basic thrust lines," explained Arup.[140] In 1957, Utzon's architecture firm joined forces with Arup to transform the design of the Opera House from a competition entry to a building.[141] However, their collaboration was troubled by differing conceptions of good form. Ove Arup and his team were concerned with structural integrity, and at the heart of this, the calculability of form. Ove Arup writes, "The interplay of surfaces made an assessment of structural feasibility by normal approximations difficult and of dubious value."[142]

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139 David Messent, *Opera House Act One* (Sydney: David Messent Photography: 1997), 260.
140 Ibid.
141 Arup was hired directly by the Opera House client, the Ministry of Public Works in New South Wales.
142 David Messent, Opera House Act One.

Figure 10. Jorn Utzon's winning entry for the Sydney Opera House competition. Anne Watson, "An Opera House for Sydney: Genesis and Conclusion of a Competition," in *Building a Masterpiece: the Sydney Opera House*, ed. Anne Watson (Sydney: Powerhouse Publishing, 2006), 50.

Utzon's team had aesthetic and expressive aspirations for the form. "I have made a sculpture -- a sculpture covering the necessary functions, in other words, the rooms express themselves, the size of the rooms is expressed in these roofs."[143]

Their interests were not necessarily contrary. However, in order for the design of the Opera House roofs to be worked on collaboratively and in order for the work to be coordinated, differing conceptions of form among Utzon's architects and Arup's engineers had to be reconciled. Despite the long term difficulties of the project, the resolution of the Opera House roofs provides a useful example through which to understand how engineers at Arup use simulation to resolve issues of form in collaborations with architects.[144]

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[143] Ibid.

[144] Jorn Utzon eventually resigned from the project under pressure from the Ministry of Public Works in New South Wales.

The term "form" has a history of contested meanings.[145] During the twentieth century, modernist architects defined form in opposition to other dimensions of design; it represented a design consideration set apart from the function, ornamentation, and social value of designs. [146] Form has been used as means of articulating the professional space of architects.[147] However, engineers and other non-architects at Arup have also made use of the term. These practitioners have developed their own approach to form, which they often define in opposition to the architectural notion of form. In Ove Arup's description of the Sydney Opera House roofs, he asserts that there are at least two ways of thinking about form: structural and architectural. Ove Arup's assertion that form can and should be evaluated by more than one standard is a way of creating a place for his firm through a conceptual difference with architecture.

Exchange between professionals often requires translation and compromise. Arup wrote, "Utzon was quite willing to change his shapes in order to reduce the [structural] moments, but any major deviation from the architect's proposal would not have been the design which won the competition… I therefore advised him to retain his basic idea and we would somehow make it work."[148] Both Arup and Utzon wanted to find a mutually satisfying resolution, but they were working with different ways of parsing and evaluating form. Utzon's team used drawings and wooden models. Arup's team used mathematics. In the

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[145] Adrian Forty traces the contested meaning of form as far back as ancient Greece. He notes that Plato's writing distinguishes between "that which always is and never becomes" and "that which is always becoming but never is." The first, writes Plato in Timaeus, is "apprehensible by intelligence with the aid of reasoning, being eternally the same." The second is the object of sensation. What is unchanging and known only to the mind is the "form," contrasted with the thing, known to sense. Plato's student, Aristotle, was reluctant to make the same sharp distinction. In Metaphysics 1031b, he wrote "Each thing itself and its essence are one and the same." Adrian Forty, *Words and Buildings: A Vocabulary of Modern Architecture* (New York: Thames & Hudson Inc., 2000), 150.
[146] Ibid.,161.
[147] Ibid.
[148] David Messent, *Opera House Act One,* 223.

Figure 11. Utzon and Arup engineers discussing a physical model. Philip Nobis, "Great Strength with extreme lightness: Utzon's Use of Plywood," in *Building a Masterpiece: the Sydney Opera House*, ed. Anne Watson (Sydney: Powerhouse Publishing, 2006), 138.

collaboration between Utzon and Arup, geometry was the basis for building a space of exchange. Geometry could bridge between the drawings and models of Utzon's office and the mathematics used to analyze the structural properties of form at Arup. Using geometry as a common basis of exchange, a means of simulating form, Utzon and Arup pursued a range of possible designs for the Opera House roofs. A concrete expert working with Arup, named Ronald Jenkins, proposed several structural shell solutions for the roofs. Jenkin's shells were based on parabolic or ellipsoidal geometries, however these were later excluded because they deviated to much from Utzon's original form, as described in the competition model and drawings. [149]

Although the form of Jenkins' structural shells did not appeal to Utzon, he accepted the medium of geometry as a means of dealing with Arup's engineers.

[149] Peter Murray, *The Saga of the Sydney Opera House: The Dramatic Story of the Design and Construction of the Icon of Modern Australia* (London: Spon Press, 2004), 30.

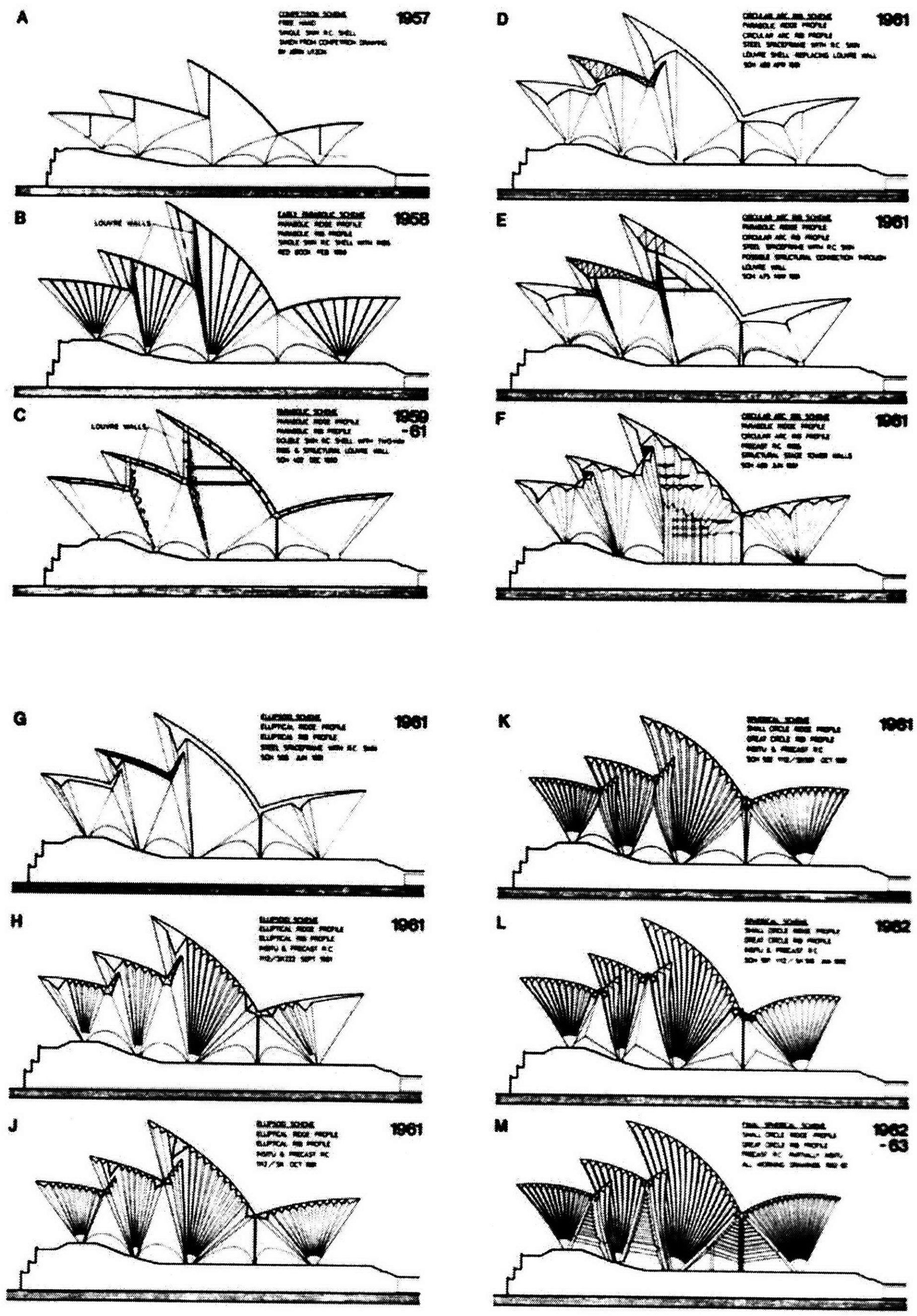

Figure 12. "Evolution of the roof from the freeform shape of the original competition design to the parabolic and ellipsoid schemes of 1959-61, to the final spherical geometry of 1962-63. In the struggle to maintain the original architectural intent some 12 different roof schemes were developed." John Nutt, "Constructing a Legacy: Technological Innovation and achievements," in Building a Masterpiece: the Sydney Opera House, ed. Anne Watson, (Sydney: Powerhouse Publishing, 2006), 109.

Even after Jenkins left the project and another of Arup's engineers, Jack Zunz, came onboard, geometry remained the central medium of collaboration. Zunz and Utzon struggled to find an appropriate geometric expression of Utzon's original form. "As far as I was concerned, the [original] geometry was sacrosanct," said Zunz.[150] However, after repeated attempts to make Utzon's competition scheme work, the "original geometry" came to be seen as a "geometric straightjacket." [151] Zunz and his team told Utzon that the only way to create a structurally and economically responsible form was to base it on a spherical or toroidal geometry.[152] Utzon eventually reformed his shells using geometry from a single sphere. The resulting form could be divided geometrically into repetitive ribs for analysis and construction. Utzon explained the form as a compromise between his values and the values of Arup.

> If you drop a big crystal ball on the floor and then pick up the pieces the top face of each piece will have the same curve. This means that the pieces are in harmony with one another, they come from the same sphere with the same radius and therefore when they are built up in space, we know that they will interact according to a natural law and that the composition is in equilibrium... We can now divide this into identical parts like slicing an orange. These become the ribs and then the ribs can be divided up into the smaller Y-shaped segments - all having the one common curve, the radius of the ball... You have here the precision of mass-production with the freedom you normally have

150 Ibid.
151 Ibid., 35.
152 Ibid., 30.

only from handmade things.[153]

Utzon embraced the form because of its "freedom". At the same time, he suggests that Arup was satisfied by the "precision" of the form. Although they maintained their individual perspectives, they converged around this spherical geometry. This space of exchange might be thought of as both a trading zone, in Peter Galison's sense and a space of alternatives, in the sense explained by Herbert Simon. The spherical geometry of the Opera House roofs allowed for both the architectural and the structural evaluation of form to be satisfied. For Arup, the spherical geometry represented a standardized, rational set of shapes that were calculable and thus could be made structural. For Utzon, the spherical geometry served aesthetic goals; it produced a compositional "harmony" among the shells. Two divergent conceptions of form were expressed, negotiated, and reconciled in the space of exchange.

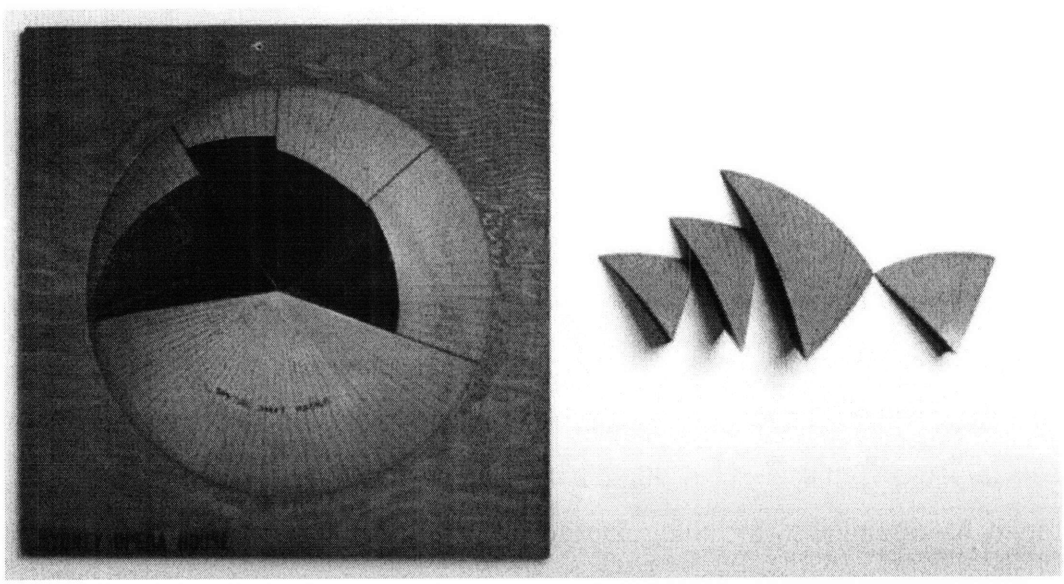

Figure 13. Utzon's Wooden Model of the Space of Exchange. Philip Nobis, "Great Strength with extreme lightness: Utzon's Use of Plywood," 138.

[153] David Messent, *Opera House Act One*, 222.

The design of the Sydney Opera House was framed by a constrained space of geometries. Parabolic, ellipsoidal, and spherical geometries formed the basis of the set of solutions that designers considered for the roof; they selected from this space of alternatives. This space was defined largely by the limitations of the structural calculation and simulation tools employed by Arup. This was the first time that Arup significantly employed computer simulations for structural analysis. Their tools could accommodate only these simple geometric representations. Arup's simulations, models, and routines for analysis put a boundary on the range of forms which were seen as possible and desirable.

In this chapter I will elaborate the notion that simulations are spaces of exchange and examine how they give increasing value to the performance of form as a measure of its value. As I move beyond the historical example of the Sydney Opera House roofs, I will explain how information technologies for simulation have been used at Arup to shape the way form is expressed, negotiated, and reconciled among design professionals. These technologies have opened new spaces of exchange in collaborative form-making. Increasingly, these collaborations are shaped by simulations which make a conceptual distinction between the intent of form, attributed to architects, and its performance, an area of knowledge claimed by practitioners at Arup.

In the example of the Sydney Opera House, the performance of form was evaluated by Arup in structural terms, using geometry as a means of exchange with architect Jorn Utzon. The examples that follow are from more contemporary projects. They highlight other descriptions of performance in a range of disciplines, including facade design, lighting, and acoustics. I will examine how these disciplines exchange descriptions of performance through various simulations: geometry, quantification, visualization, and auralization.

The Intent and Performance of Form

Arup's renovation of The Wexner Center for the Arts provides a contemporary example of the use of geometry as a space of exchange in design. In the case of the Wexner, the exchange was between the Arup Facade Group and the Wexner Center administration. The Wexner Center is a museum in Columbus, Ohio. Architect Peter Eisenman, a practitioner and academic, won a competition to design the Wexner. Eisenman's design was constructed in 1989, closed in 2002 for renovations guided by Arup, and reopened in 2005. Eisenman was not involved in the renovation.

Arup's relationship with the administration of the Wexner Center was defined around a formal objective, to change the environmental performance of the museum while retaining the intent of Eisenman's form. Sarah Geldin, director of the Wexner Center explains "This is a landmark of kind of architectural practice at a certain point in time. We recognized the importance of preserving the architectural intent."[154] Eisenman's form, as intent, was considered sacrosanct. It is piece of the museum's collection, says Roger Chang, a young mechanical engineer working with the Arup Facade Group. The performance of the form was another matter; Arup's task was to alter the environmental performance fundamentally. In Arup's report to the Wexner Center, Roger Chang explains, "The computational modeling undertaken shows that the use of a high performance curtainwall and skylight system in conjunction with a redesigned mechanical system will allow stable temperature and humidity to be maintained in the Wexner Center galleries." The goal of the Wexner Center director was to preserve Eisenman's intent. Arup's goal was to establish a stable temperature, lighting, and humidity in the galleries. The overlap between these goals, the

[154] Nicolai Oursousoff, "An Engineering Magician, Then (Presto) He's an Architect," *New York Times*, November 26, 2006, Design Section.

Figure 14. Interior of the Wexner Center for the Arts. Massimo Vignelli, *Wexner Center for the Visual Arts, The Ohio State University,* (New York: Rizzoli International Publications, Inc., 1989), 201.

common ground between intent and performance was a geometric model of the building. Arup took the geometry as the intent. They changed the performance with only minor alternations to the geometry.

From a geometric perspective, the form of the museum is highly unconventional. "There were few right angles," says Roger Chang.[155] Eisenman's building started the wave of crazy looking art museums.... other museums were just big boxes."[156] Forty describes Eisenman's motivation as a "crusade against functionalism."[157] Using form as the "instrument of attack," Eisenman designed

[155] Roger Chang, interview by the author, 2006.
[156] Ibid.
[157] Adrian Forty, Words and Building: A Vocabulary of Modern Architecture, 168.

the Wexner as a manifesto against traditional museum typologies.[158] However, the interior environment of the building was ultimately deemed unsatisfactory by the museum directors. The Wexner could not maintain a constant temperature. No thermal breaks in its aluminum framed facade meant there were forty degree fluctuations. There were leaks and areas of condensation. The intensity of natural light in the building was overwhelming, especially for the artwork.[159] The Wexner presents an extreme disconnect between two meanings of form, as performance on one hand and as intent on the other. This distinction echoes a long standing philosophical debate. Is form a "shape" or is it an "essence."[160] Forty explains that "one describes the property of things as they are known to the senses, the other as they are known to the mind."[161] We might say that the essence of the Wexner form was highly prized by the museum administration. Meanwhile, its shape, the form as it is known to the senses in terms of temperature, humidity, and light, was problematic. This distinction is familiar and easily accepted by clients and architects. In Eisenman's explanation to the New York Times of why he was not involved in the Wexner renovation, he maintained that the performance problems of buildings are not his concern as an architect.[162]

Under the weight of the Wexner's performance problems, the museum decided to close its doors, 13 years after its opening. In 2003, Arup was commissioned to repair the performance of the building.[163] The Arup team

[158] Ibid.
[159] Low E coatings weren't available to shield the building from the sun, only heavy tints or reflective coatings.
[160] Adrian Forty, Words and Building: A Vocabulary of Modern Architecture.
[161] Ibid.,160.
[162] Nicolai Oursousoff, "An Engineering Magician, Then (Presto) He's an Architect."
[163] Arup was originally hired to perform an analysis on a proposed renovation of the space designed by a local engineering firm. However, Arup engineers were appalled when they saw the proposed scheme. Local engineers were suggesting highly unconventional, and risky quick fixes for the problems of the museum. Arup told the museum that, for a little more money, a new system could be installed. The museum was convinced and hired Arup to redesign the curtain wall and other building systems.

accepted the commission with the goal "to not compromise Eisenman's design."[164] At the time of the museum's construction, geometrical descriptions of the Wexner Center were unmanageable. In geometrical terms the Wexner was too ambitious, says Chang. The existing building systems and analysis tools could not support the geometry. Computational fluid dynamics techniques for assessing the interior environment were not widely available. Without proper analysis tools, the original engineers could only follow best practices. Unfortunately, Eisenman's form didn't allow for this. The Wexner was designed to challenge conventions of form.

When Arup took on the renovation, they were just starting to assemble the simulations necessary to handle the geometry from a performance perspective. The Wexner Center renovation was the first project in which they brought to bear different simulation types on the analysis of one facade. Arup still had some problems with the geometry. But, their suite of integrated simulations made most of Eisenman's geometry viable. On the Sydney Opera House, there was a very narrow space of exchange between Arup and Utzon. They had to change the geometry of the Opera House roofs significantly in order to suit the constraints of structural performance testing. On the Wexner Center, Arup was able to maintain the geometry, more or less, and still make performance changes. With new modeling software and simulations, geometry has been expanded as a space of exchange.

[164] A review of this project can be found in Robin Pogrebin, "Extreme Makeover, Museum Edition," New York Times, September 18, 2005, Design Section.

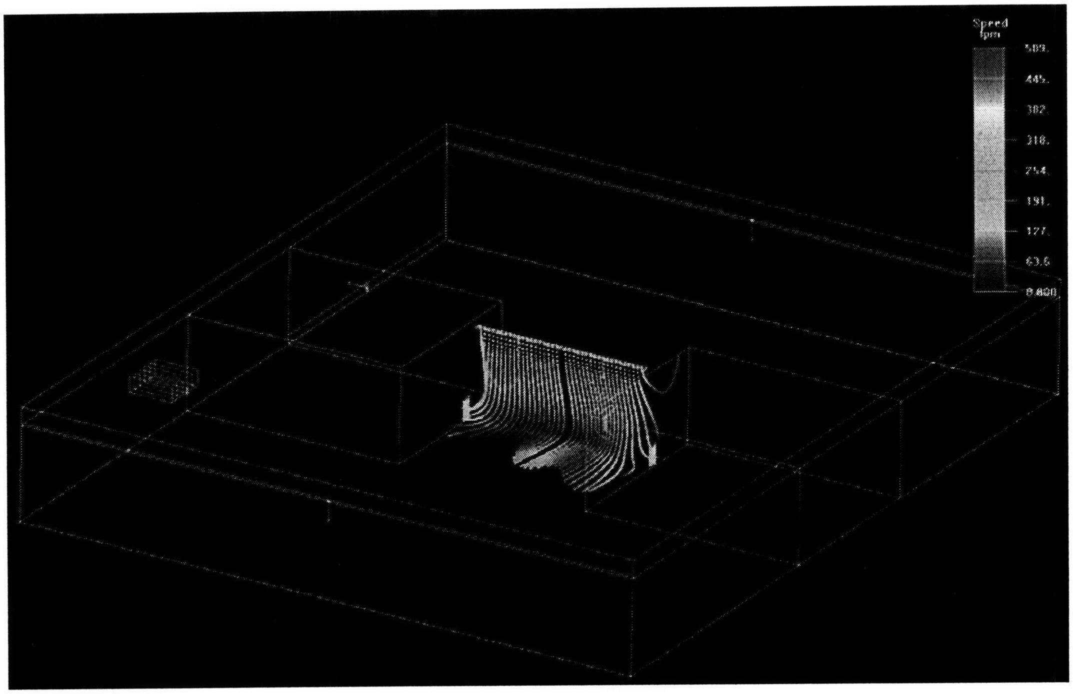

Figure 15. Wexner Center for the Arts. Air curtain particle trace using Airpak. Image courtesy of Arup.

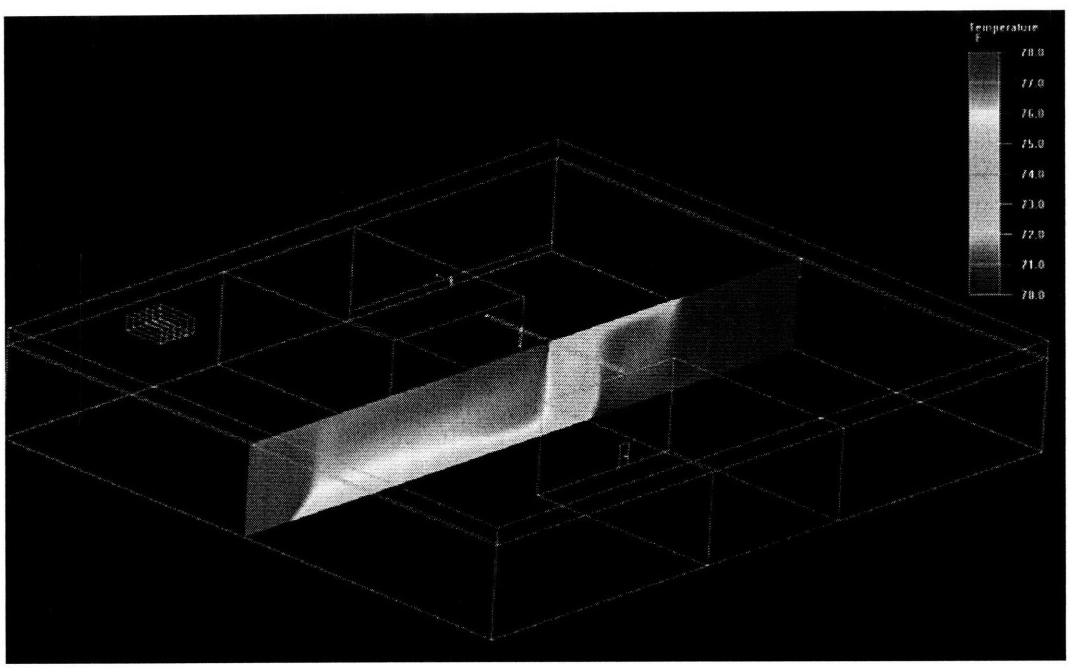

Figure 16. Wexner Center for the Arts. Summer temperature contours using Airpak. Image courtesy of Arup.

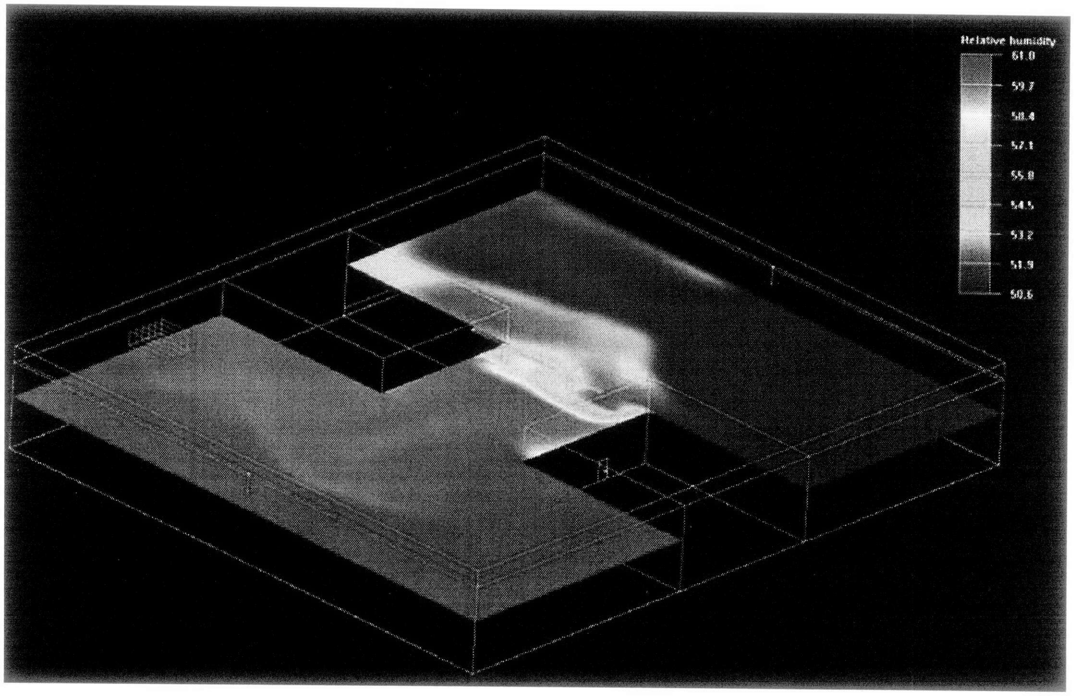

Figure 17. Wexner Center for the Arts. Summer relative humidity using Airpak. Image courtesy of Arup.

In the case of the Wexner, simulations articulated the original form in a new way. Arup used simulations to distinguish between form as intent and form as performance, and thus create a place for themselves in the Wexner Center renovation. This place was established through their relationship to the Wexner Center administration. Arup's simulations were tailored for an audience of museum administrators. Their simulation results were presented in a report explaining their analysis and their recommendations for the museum renovation. Eisenman did not participate in the renovation, but he gave his blessing to the project and accepted Arup's proposition that the intent of the Wexner form and its performance could be separated. By suggesting subtle design changes, primarily to the facade and mechanical systems Arup created a stable performance for artwork and visitors, while preserving the what the director of the Wexner Center referred to as the intent of Eisenman's form.

Lighting Performance

Among the many problems of the Wexner Center interior environment was the amount of natural light permitted to fall on the artwork. The light levels in the Wexner defied standard, numerically-defined rules of lighting art. For instance, twenty foot-candles is the standard illuminance level for an oil painting.[165] One of the established references for setting light levels in museums is *The Museum Environment*, by Gary Thompson.[166] The guide was first published in 1978. Arup lighting designers call this their bible. Arup recommendations to the Wexner Center, outlined in their final report include shading devices to change the performance of light in the museum. In Arup's report, good performance and good form are defined in numerical terms, using guidelines like those in Thompson's book. In the case of the Wexner renovation, the exchange between Arup and museum administrators was not only geometric, it also included the exchange of numerical representations of performance.

Often the Arup Lighting Group begins its collaborations with architects at the conceptual design phase. Their incorporation of numerical standards for light levels in museums has lead to some startlingly complex forms, like the roof of the Nasher Sculpture Center in Dallas, designed with Renzo Piano's architectural office. These complex forms are the result of a design process aimed at producing the right illuminance levels inside. Matt Franks, a Senior Lighting Consultant at Arup New York explains how on recent museum projects like the Nasher Sculpture Center and the High Museum of Art in Atlanta, Arup worked with architects to develop fenestration and shading systems that would block all direct

[165] One foot-candle is the illuminance on a one sq.ft. surface under a uniformly distributed flux of one lumen.
[166] Gary Thompson, *The Museum Environment* (Oxford: Butterworth-Heinemann, 1978).

natural light and UV rays.[167] These systems are designed to allow only indirect, filtered illumination to reach the artwork. In both cases, the design process revolved around mutually acceptable simulations and the goal of preserving a consistent illuminance level in these museums all year round. "What gets inside remains constant" says Franks.[168] The goal was to create consistent experiences inside these museums.

Figure 18. Nasher Sculpture Center roof exterior. Image courtesy of Arup

[167] Matt Franks, comments made in a lecture at MIT on April 4, 2008.
[168] Ibid.

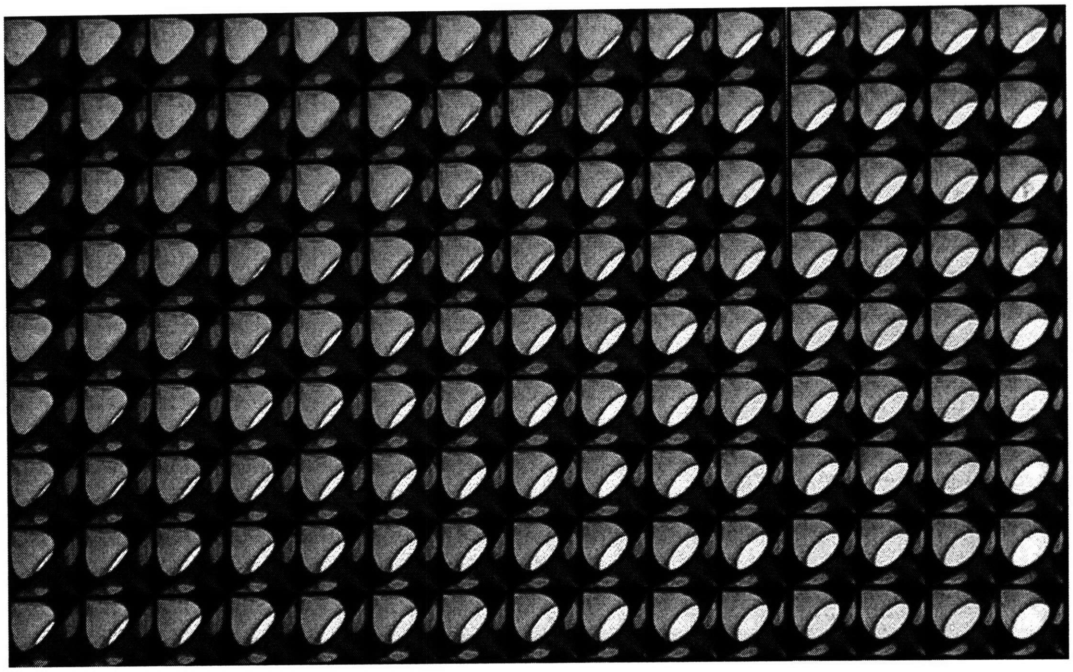

Figure 19. Nasher Sculpture Center roof interior. Image courtesy of Arup

On another project, the North Carolina Museum in Raleigh, designed with architects Thomas Phifer and Partners, artificial and natural light are blended through a translucent dropped ceiling in order to achieve a consistency which satisfies a quantitative value assigned to protect the artwork. For museum curators, consistency means flexibility. Franks says light levels are "optimal" throughout the space.[169] When the light levels are constant throughout the museum, curators can place art work almost anywhere. Through the use of numerically-oriented lighting simulations, the performance of light in the North Carolina Museum of Art was made homogenous. Aesthetically, the museum is a neutral realm for the display of artwork.

Numerical-oriented simulations are not the only representations brought by Arup to the service of lighting design. Computer models, paper models, scale models and full scale mockups are all used in conjunction. Together, they give

[169] Ibid.

visual, geometric, and experiential feedback to designers. However, the foot-candle value remains a powerful means of describing light. The numerically established illuminance levels specified by Thompson and others shape the space of exchange in which architects, Arup lighting designers, and museum curators can agree on what form of lighting is most appropriate. The discourse of illuminance gives preference to a discussion of museum forms in terms of performance. The Nasher Sculpture Center, the High Museum of Art, and the North Carolina Museum of Art were designed with attention to numerically defined performance. Their aesthetics with respect to lighting have converged around the singular objectives of admissible illuminance levels. At a lecture by Franks at MIT, Professor William Porter expresses an emerging concern among architects that using numerically-oriented simulations is narrowing the space of exchange in which practitioners evaluate the quality of light in museums. "Do we lack the vocabulary to deal with a diverse range of lighting conditions?"[170]

More recently, museum projects by Arup are moving beyond the goal of optimization and reliance on quantitative values. In an ongoing building project with architects Herzog and de Meuron, the Arup Lighting Group aims to bring the natural light directly into gallery spaces. Artwork will have to be arranged with consideration for the resulting dynamic lighting conditions. The project represents a break with Arup's typical approach to lighting in museums and its reliance on numerically-oriented simulations. Together, Arup and Herzog and de Meuron are broadening the range of acceptable lighting aesthetics in museums.

The importance of illuminance values in contemporary museums recalls the focus on reverberation time in concert halls at the beginning of the 20th century. At that time, the Sabine's equation, a simple simulator for estimating the reverberation time of sound in buildings opened a new numerically-oriented space

[170] William Porter, , comments made from the audience of a lecture by Matt Franks at MIT on April 4, 2008.

of exchange between architects and acousticians. According to Raj Patel, the director of the Arup Acoustics Group in New York City, this set up a narrowly defined interaction between practitioners. According to Patel, the interaction was "one dimensional."

> [Sabine] said, I'm giving you an empirical formula to which you attach a single number. The acoustics of the room are defined by the reverberation time and the reverberation time target of your room needs to be any number which you could go and measure quite easily and therefore you need to put this amount of sound absorption treatment in your room to meet that number.[171]

Sabine's equation :

$$t = \frac{.164\ V}{\sum (a_n\ s_n)},$$

where:

t = reverberation time (in seconds),
V = volume of room (in cubic meters),
a_n = absorption coefficient of material n, and
s_n = surface area of material n (in square meters).

Figure 20. The Sabine Formula from Emily Thompson, The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900-1933, 41.

Subsequent to the introduction of Sabine's formula, reverberation time became the basis for a new system of evaluating concert halls, but also a driver in the development of new designs. Historian Emily Thompson writes about how

[171] Raj Patel, interview by the author, 2006.

during the twentieth century, low reverberation times became the acoustical goal a whole range of building projects. Measures like illuminance and reverberation time represent performance in quantitative terms, amenable to comparison and control. However, there is a danger that numerically-oriented simulations are aesthetically constraining. They may lead to the design of forms which seem different in intent, but perform in a homogeneous manner.

The Visualization of Form

Outside of the strict context of museum design, illuminance values are given less prominence. Visualizations, computer generated renderings, have opened a range of new discussions about "what light is doing," says Steven Walker, a British lighting designer working at Arup's London office.[172] Radiance is currently the predominant simulation in use within Walker's group. The simulation is a collection of tools in UNIX, "almost a way of thinking, more than a single piece of software," explains Walker.[173] Radiance was immediately accepted within Arup because of its ability to deliver photo-realistic renderings and the promise of predicting visual experience. Although Radiance can also generate predictions of performance in terms of illuminance values, the simulation's images are of interest because they have enabled a new space of exchange between the Arup Lighting Group and its clients and collaborators. Initially, explains Walker, architects were nervous about accepting visualizations, especially at early phases of the design process. Walker speculates that it was probably the Mercedes Benz Design Center in Sindelfingen, Germany designed

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[172] Steven Walker, interview by the author, 2007.
[173] Ibid.

between 1993 and 1998 that "put lighting on the map."[174] I take Walker's statement to mean that lighting became accepted both as a technical practice -- the Arup Lighting Group gained acknowledgement -- and as a perspective on the performance of form.

Renzo Piano was hired by Mercedes as the architect for their Design Center in Sindelfingen. One of Mercedes' directives was that the Design Center must have studios where car designers can build full size models of their designs. This directive came with one major constraint. As a matter of standard practice, spaces designed for such modeling work have no natural light; they have artificially controlled lighting. Car designers routinely use the reflections of parallel, tubular ceiling lights to analyze the complex curves of cars under design. By examining the way that reflections are distorted on the curved surfaces of their models, car designers can determine the implications for manufacturing such surfaces on a mass scale. Renzo Piano's architects challenged the assumption from administrators at Mercedes that natural light would interfere with this process. The architects searched for a way to bring daylight into Mercedes studio spaces without disturbing the ability of car designers to conduct their curvature analysis. The designers at Mercedes were apprehensive.

Arup suggested the use of their new photorealistic visualization techniques in order to evaluate how daylight might interfere with curvature analysis. In order to convince Piano's architects and Mercedes' administrators and designers, Arup introduced Radiance. Arup lighting designers would meet with Piano to discuss the lighting approach, then carry out analysis on the agreed upon scheme. Using Spark Sun workstations with 24 megabytes of ram and 386 processors, it took 5 full days of rendering time for Walker to produce each rendering variation.

The resulting images shaped a new space of exchange and evaluation among the

[174] Ibid.

design participants. By using photorealistic visualization techniques afforded by Radiance, Arup lighting designers were able to convince clients through a set of images that daylight from the windows proposed by Piano would not interfere with the readings of reflections.[175] The form of the Mercedes Design Center was

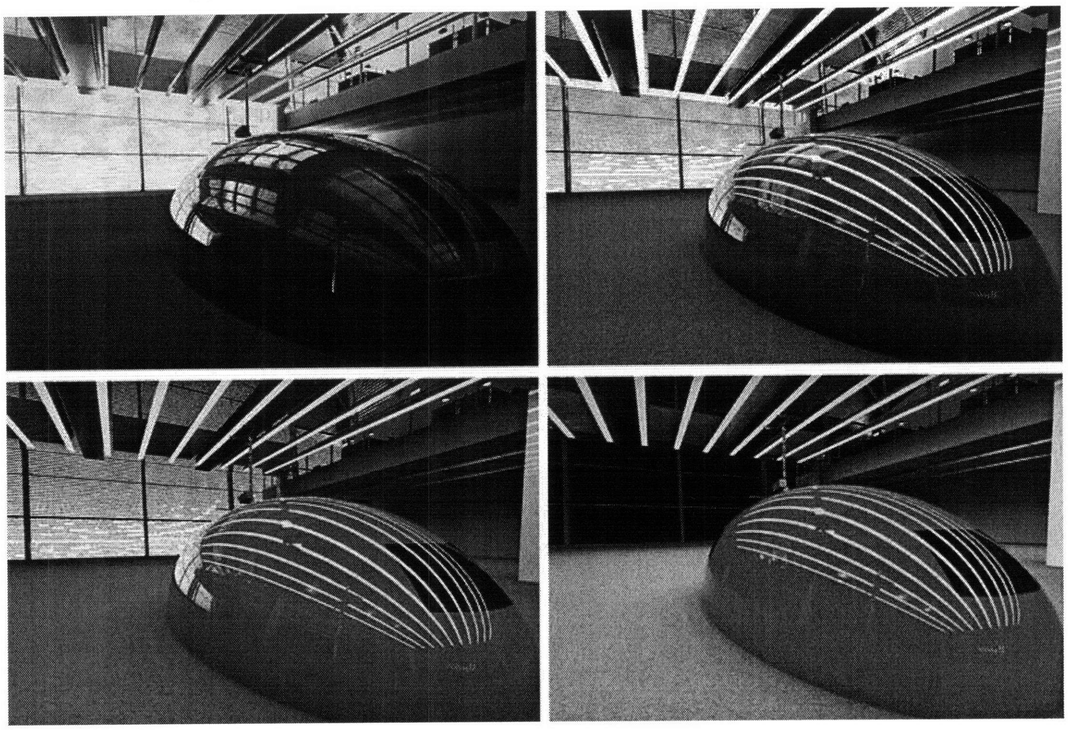

Figure 21. Arup Renderings of Mercedes Benz Design Center. Image courtesy of Arup.

[175] Today, architects also use many rendering tools, however these are generally non-analytical, according to Andrew Sedgwick, Walker's boss and the director of the Arup Lighting Group in London. Architects know their tools are not photometrically correct, says Sedgwick. Typical problems with this software, like 3-D Studio Max, are that they will not calculate light precisely, primarily because its computationally intensive to render things properly. You also need to know the details of the light fixture, the materials, the place, time, etc. It comes down to refinement, like knowing where are the critical areas to increase the computational mesh, the resolution of the analysis.
Contrary to Sedgwick's statement, Robert Stava argues that "software like 3ds Max is now capable of doing accurate lighting analysis (Something I and my colleague Anthony Cortez demonstrated at an Autodesk MasterClass at Siggraph 2006, after tutoring by our NY Lighting team). It uses photometric lights, renders in 16 or 32 bit file formats and it's material functions allows accurate reflectance and transmittance values to be adjusted and set same as Radiance. It's closing the gap very rapidly as an valid simulation software." Robert Stava, e-mail correspondence with the author, 2008.

resolved through the simulation of visibility in the room. They created a space of shared experience.

Today those simulated images produced using Radiance look crude. We wouldn't call them photo-realistic. One problem with such images is that they can never duplicate the level of contrast in a real scene. Imagine driving through a long dark tunnel and emerging into daylight. Direct sun in the summer can reach 10,000 foot-candles. The blinding experience of seeing the sun for the first time after being immersed in darkness cannot be replicated by an image. Today, our expectations of virtual reality are much different. At the time Arup's renderings validated Piano's form from a performance perspective. These images were accepted as predictors of visual experience in the Mercedes studios.

Walker explains that it was the personal relationship between Renzo Piano and Tom Barker, the project leader at Arup that enabled thee images to function as a medium of exchange. Piano just trusted Barker to provide a valid demonstration of the lighting in the space. Meanwhile, Barker knew how to create a simulation that would satisfy Piano's idiosyncrasies. Piano hated looking at the screen, so Barker spent a large sum of money printing out each rendering on paper. For Piano, it was important to be able to hold the renderings and interact with them. "You have to take into account the idiosyncrasies of people," explains Walker.[176] Simulations which demonstrate the performance of form must be tailored for a particular audience. In the case of the Mercedes Design Center, Arup was able to negotiate a role for itself in the evaluation of form because its visualizations met the expectations of both collaborators and clients.

[176] Steven Walker, interview by the author, 2007.

The Auralization of Form

The Sound Lab is one of the most convincing virtual reality machines that Arup possesses today. It is one of few simulation tools at Arup that has been written about widely in professional journals and popular publications like the New York Times. Raj Patel, the director of Acoustics at the New York office of Arup, explains that acoustical simulations or auralizations produced in the Sound Lab allow form to be explored as an acoustical experience. "People are rediscovering things about the architecture that made the room sound the way it sounded and therefore how to design concert halls."[177]

For Patel, immersive simulations render experience concrete. Simulations enable acoustical experiences of the past and present to be exposed, analyzed, compared and tinkered with. Historian Emily Thompson has written about acoustical simulation as a postmodern soundscape, in which "the past -- be it gothic, baroque, or modern -- [is] like an endlessly stimulating old album of phonograph recordings from which we are privileged to pick and choose."[178] Architects and clients can choose among a history of acoustical experiences or simply tinker with the form. Patel explains, "If you can get the spacings right, suddenly the room sounds huge and expansive and wide. The sound lab allows us to play with dimensions to see how they fundamentally affect the way that we hear."[179]

Patel was trained as both a physicist and a classical musician, but at Arup, he is also a design professional. Professing an understanding of form in terms of

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[177] Raj Patel, interview by the author, 2006.
[178] Emily Thompson, *The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900-1933* (Cambridge: MIT Press, 2004), 324.
[179] Raj Patel, interview by the author, 2006.

acoustical performance has enabled Patel and his colleagues to establish powerful roles among both architects and clients. The Arup Acoustics Group has created a place for itself within the conceptual, form-finding phases of many design projects by leveraging the use of the Sound Lab. Alban Bassuet, a young acoustician at Arup, explains how the firm's acoustical simulations triumphed over those of a competitor, Jaffe Holden.

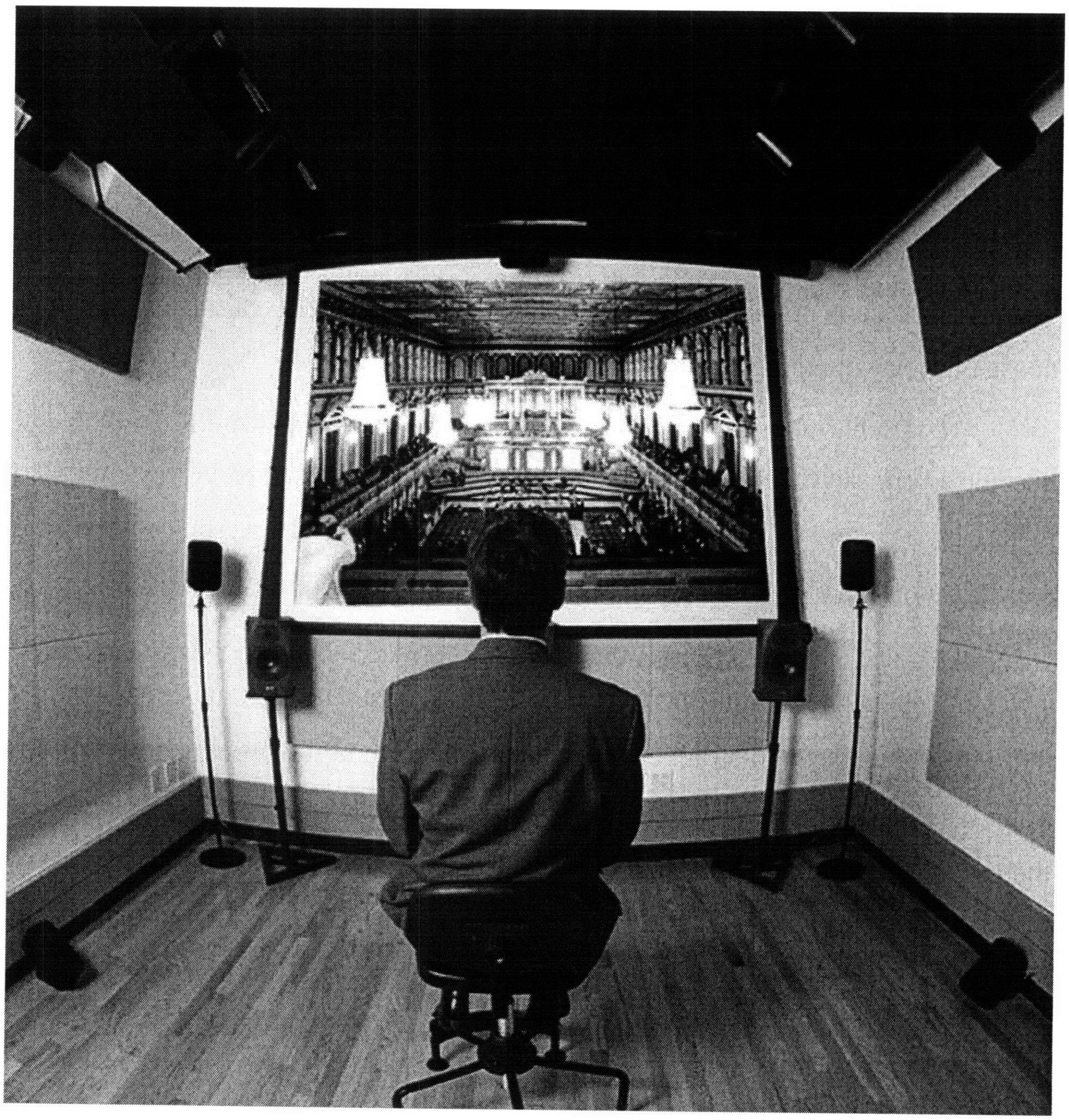

Figure 22. The sound lab. Image courtesy of Arup.

"Their tools are not as sophisticated," asserts Bassuet during my first visit to his office in New York.180 Arup is competing with Jaffe Holden in the context of the first major renovation of Lincoln Center's Alice Tully Hall since it's opening in 1969. Jaffe Holden was originally selected to design the new acoustical experience of the hall. Arup was hired separately, as consultants to the architects of the renovation, Diller, Scofidio and Renfro, in order to address a number of other technical issues like structures, ventilation, electrical and plumbing systems, and fireproofing. Using a suite of acoustical models and simulations, some of which were developed in-house, Bassuet and his associates challenged Jaffe Holden's exclusive authority over the acoustics of the renovation. "The clients wanted to be here," recounts Alban Bassuet.[181] "They trusted us." "[Jaffe Holden] doesn't have a sound lab like this one."[182]

Over the course of the Alice Tully Hall renovation, Arup's sound lab became a primary space for design decision-making. The success of the sound lab is part of a culture at Arup of using simulation to bring designs into the virtual realm as a means of gaining greater control over the form of designs.

How can acoustic experiences be identified, evaluated, replicated, and controlled as a dimension of building performance? The acoustics group at Arup explores these questions through a range of techniques, including the prominent use of the Sound Lab. Arup acousticians originally intended to use this device for themselves. Bassuet explains that the Arup acoustics lab was built "so that we can listen to our designs."[183] However, the room eventually became popular with clients, musicians, and architects. Now it serves as a primary setting for discussions on acoustics among diverse groups of design participants. The Sound

[180] Alban Bassuet, interview by the author, 2006.
[181] Ibid.
[182] Ibid.
[183] Ibid.

Figure 23. Rendering of Alice Tully Hall. Diller, Scofidio and Renfro, "Juilliard Construction: Floorplans and Renderings," The Juilliard School, http://www.juilliard.edu/utilities/construction/floorplans_renderings.html

lab enables acoustic experience to be the space of exchange among them.

> The thing about the sound lab is that you've got everybody in the same room at the same time. They all hear exactly the same thing. You have the discussion in the room. You make the design decisions then you move on, so it's a much more collaborative process.[184]

[184] Raj Patel, interview by the author, 2006.

The sound lab is a small room, approximately a cube, with interior dimensions of about 10' x 10' x 10' with 12 speakers positioned on the walls and ceiling. It relies on the principle of auralization to create an aural rendering of a space. An impulse or "click" is first emitted in a real space or in a computational model of a space. The resulting reverberations are measured and used to create an acoustical signature for that room. Another sound (usually a piece of music) is then recorded in an anechoic chamber, a room that absorbs all sound and effectively has a reverberation time of zero. The reverberation time is the time it takes for an emitted sound to decay below a set point. It is based on the room volume and the absorption of the room. "In a good anechoic chamber," says Bassuet, "you can hear the blood pumping in your veins."[185] The perfect chamber would be so unnatural that it would make you sick just to be there. The recorded music is then augmented through a process called "convolution." The resulting music is what you hear in the sound lab, a simulation of what the anechoic performance might sound like in the real hall or computational model that you started out with. Bassuet calls this a "spatialization" or the "rendering of space."[186]

In one of my tours of the sound lab, I sit amidst a class of undergraduate architects from City College, led by Jessica Strauss, a thirty-something architect who works at Arup and teaches at City College part time. Strauss's students have come to Arup's office for an experience of professional practice. Ryan Biziorek, an employee at Arup, has been tasked with giving a simple demonstration of the sound lab. Biziorek is in his twenties and a recent hire at Arup.

On a projection screen in front of us, Ryan presents two virtual models. He calls these "boxes," not concert halls or buildings. On one side of the display, he shows us a "narrow box." This box has a reverberation time of 2.0 seconds says Ryan. On the other side of the display is a "wide box" with the same

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[185] Alban Bassuet, interview by the author, 2006.
[186] Ibid.

reverberation time, also 2.0 seconds says Ryan. The fledgling acoustician puts Handel's Water Music on the sound lab speakers as it would be heard, first in the narrow box, then in the wide box. Following the demonstration, he asks for our impressions. "What do you hear?" "What do you like?" We are silent. We lack the vocabulary to express our impressions about the sounds we just heard.

Let's examine what is happening in this scenario. How do you talk about an acoustic experience without a shared vocabulary? For an experience to be objectified, it must first have a language. Discrete acoustic experiences and their attributes must be identifiable in a common way. One reoccurring problem is that acousticians and architects have different meanings for words like "tone," "clarity," and "intimacy." These are multivalent terms. For example, architectural intimacy might have to do with the physical proximity between the musician and the audience. Meanwhile, acoustic intimacy may concern the reverberation time that the audience experiences. If the audience is close to a reflective surface, they can experience acoustic intimacy; it will sound as if they are close to the musicians, even if physically they are not close. So at the back of a concert hall, it is possible to have acoustic but not architectural intimacy. Such demonstrations are meant to develop of a local exchange language, what we have been calling a space of exchange. Biziorek and Patel both concur on this point.

> The interesting thing about it, is that you have to develop a common language. What we mean by certain words: direct sound, reflections, reverberance, envelopment, proximity, intimacy. All of those words mean different things to different people. So the first part of the conversation is always the basic demonstration that you had, to get some commonality and some understanding in the words that you are using. So that they understand what we mean,

then using that in discussion.[187]

Bassuet, in contrast, says that the room "does away with linguistic vocabulary." But linguistic vocabulary does not go away in the sound lab, it spreads in a very short period of time. So why does Bassuet say that the room does away with linguistic vocabulary? Perhaps he means that the vocabulary appears transparent. In the Sound Lab, vocabulary is used as a pointer to shared experience. In this setting, vocabulary may appear transparent, because we can make a direct link between words and virtual experience.

This transparency is made possible by the conception of a common, objective experience. Michael Reddy, an early researcher in the field of cognitive science, argues that given a vocabulary we must each construct our own meanings from a repertoire of experiences.[188] The conception of a common experience in the sound lab aides in the adoption of a common linguistic vocabulary and reciprocally a shared linguistic vocabulary aides in the acceptance of the experience of the sound lab as an objective, shared phenomenon.

Once a common language is developed, design participants can identify distinct experiences and their salient characteristics. Experiences can be compared. The ability to perform this kind of shared comparison is the payoff of developing a common language within the sound lab. The result is a more controlled conversation.

> The discussion is always a very healthy flow when you are in that room, because everybody's heard the same thing… you've got eight options on the screen…, then they listen to the subtleties and

[187] Raj Patel, interview by the author, 2006.

[188] Michael Reddy, "The Conduit Metaphor" in *Metaphor and Thought,* ed. Andrew Ortony (Cambridge: Cambridge University Press, 1993).

work out the answer and it's done in two hours.[189]

What makes a simulation different from other static rationalizations, like perspective?[190] Simulations differ in their ability dynamically respond to user interaction. Simulations appear to give you control over the parameters of experience.

Back in the sound lab, Ryan demonstrates how variations in the design of a subway station can be compared and evaluated. The central acoustical problem of subway stations is that they are too reverberant. An announcement on the loudspeaker is engulfed in reverberance after the first couple of words. After that, you usually can't understand anything else that is said. Ryan pulls up a prepared simulation of the public announcement system in the 2nd Avenue Subway Project in New York City. He constructs the experience of the impaired public announcement system by layering sounds in the following sequence:

Voice Alone
Voice + Microphone
Voice + Microphone + Booth Noise
Voice + Microphone + Booth Noise + Speaker
Voice + Microphone + Booth Noise + Speaker +
4.0 s Reverberation Time of the Station and Station Noise.

With each layer, the sound gets worse and more distorted. At the end, the voice is almost totally drowned out and unintelligible. Then he demonstrates the fix, by working backwards:

[189] Raj Patel, interview by the author, 2006.
[190] For an explanation of the origins of perspective see William Ivins, *On the Rationalization of Sight, with an Examination of Three Renaissance Texts on Perspective* (New York: Da Capo Press, 1973).

Isolate the Booth and the Cable
Improve the Microphone
Improve the Speaker System
Improve the Reverberation Time

By defining an external, replicable acoustic experience and taking it apart, one component at a time, Ryan constructs the problem of the 2nd avenue subway terminal. This demonstration creates an intimate connection between words and signals, between talking about designs and experiencing them in the sound lab.

In *Soundscapes of Modernity*, Emily Thompson writes about how conceptions of sound shifted along with acoustical technologies during the early Twentieth Century.

> Acoustical technology in the modern era had been dedicated to eliminating the effect of space and replacing it with one best sound, the modern sound. Postmodern acoustical technologies, in contrast, summon forth the sound of space so easily and in so many varieties, we hardly know what to listen to first.[191]

Arup acousticians have capitalized on postmodern conceptions of sound. They have turned the exploration of varied acoustic experience into a competitive niche in the world of design. Patel articulates how the sound lab is used control the value of design through the identification of design with controllable

[191] Emily Thompson, *The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900-1933*, 324.

experience.[192]

> Every single aspect, if you start thinking about how the outside noise relationship relates to the inside noise relationship, how the design of this partition relates to how much sound goes from room to room, what the acoustics of this room are like. Every element of that can be broken down, can be explained, can be subjectively value engineered. The term value engineering is a misnomer because people will try to reduce the cost of something, but that often means putting a value on whether something is necessary or not necessary in a design.[193]

What does it mean to say that the sound lab is used to put a value on design? Simulations like the Sound Lab contribute to the production of contemporary conceptions of form in complex ways, without necessarily imposing a strict value system. As I discussed in the last chapter, the evaluation of performance at Arup is a dynamic play between simulation and other ways of knowing.

Conclusions

Spaces of exchange enabled by information technologies for simulation articulate form in new ways. Using simulations to identify new conceptions of form is akin to what Donald Schön calls "problem setting." According to Schön

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[192] "Anybody can build a building," says Alec Milton of Arup, "but it takes an engineer to make it economical." Simulations present engineers with new avenues towards discovering the most economical design. With the use of auralization, the calculation of economic value has become a matter of valuing experience.
[193] Raj Patel, interview by author, 2006.

this is "a process in which, interactively, we name the things to which we will attend and frame the context in which we will attend them."[194] Engineers are often attributed the role of mere "problem solvers" by architects. However, in the past few decades, engineers and other technical consultants at Arup have use simulations to establish new discourses on form; they have shown themselves to be problem setters by establishing new expectations for form, like structural, environmental, visual, and aural performance.

In recent years, Arup practitioners have focused on using information technologies for simulation to develop new abstractions for dealing with form as a generator of human experience. These simulations appear to give you control over the parameters of human experience. They are being used at Arup to assign economic, functional and aesthetic value to human experience. Good form at Arup is increasingly about form as it is known to the senses, through experience. Arup makes efforts to educate regulators, architects, and clients about the value of such simulations. Developing new abstractions to deal with form as experience is part of a competitive strategy at Arup. Sociologist Andrew Abbott has written about the power of abstractions in professional negotiations for jurisdiction and authority.[195] He writes that abstraction is the means by which professional define their domain of work and defend it against competitors.

Geometry, numbers, images, and sounds: these abstractions are being used at Arup to initiate new discourses on form and new spaces of exchange with clients, collaborators, and regulators. Geometry has a legacy of use as means of describing form in terms of ideal proportions and aesthetics of composition. Although simulations in use at Arup are often still grounded in geometry, these simulations give preference to predictions about building performance and experience over intrinsic geometric relationships.

[194] Donald Schön, *The Reflective Practitioner.*
[195] Andrew Abbott, *The System of Professions: An Essay on the Division of Expert Labor.*

Numerically based discourses on form are typically propagated through industrial standards, governmental regulations and "good design" guides. These discourses are useful for comparison and control, for establishing consistency. However, numerical evaluations of form are typically both reductive and opaque. Measures like illuminance and reverberation time represent intangible aspects of experience in quantitative terms. However, there is a danger that numerical trading zones may lead to the design of increasingly homogeneous experiences in buildings. Numerical trading zones can result in impoverished discourses about form. Increasingly, Arup is using a broader array of simulations to challenge numerical models of good form.

Visualizations have opened a range of new discussions about "what light is doing," Visualization offers the experience of seeing an image as an evaluation of the actual spatial experience. Radiance was immediately accepted within Arup because of its ability to deliver photo-realistic renderings and the promise of predicting experience. Their architect collaborators were more nervous about accepting renderings, especially at early phases of the design process. Today those simulated images produced using Radiance look crude. We wouldn't call them photo-realistic. Our expectations of virtual reality are much different. This is because trading zones are created for a time, a place, and specific participants. The same meanings do not hold outside of the trading zones established through a combination of simulations but also discourse and expectations. The validity of an exchange space constructed around a simulation depends a lot on who is involved in the exchange. People have to be receptive to a new space. They have their own idiosyncratic or cultural criteria for working in it.

The Sound Lab is a space both physical and conceptual in which form can be examined as a generator of aural experience. Arup acousticians, their collaborators, and clients can tinker with form and its experiential implications in a novel way. Using the sound lab does not necessarily lead to new built forms.

However, it broadens the range of forms which are available for evaluation and the means of evaluation for design practitioners.

The last chapter was an introduction to performance-based knowledge. This chapter has examined how forms are attributed different kinds of performance. The ensuing chapters will explain how the construction of performance at Arup has enabled a new discourse on professional identity to emerge.

CHAPTER 3 CONCEPTIONS OF IDENTITY AT ARUP

"The problem with old school acoustics using the Sabine formula, is that you were doing acoustics in a very one dimensional way," explains Raj Patel.[196] According to Patel, the Sabine formula, a numerical means of simulating architectural acoustics, constrains professional relationships between acousticians and architects. "You were having to do the calculations and then say to the architect, this is what's wrong with your room." [197] Patel associates Sabine's formula, a simple equation derived a century ago to predict the reverberation time of sound in a room, with "old school" acoustics and outmoded, unproductive professional roles. The formula set up a narrow space of exchange between acousticians and architects. The space of exchange was "one dimensional," says Patel.[198]

Today, Patel and his team of acousticians at Arup are trying to expand the space in which acousticians and architects collaborate through the use of the sound lab, their immersive acoustical simulator. The sound lab is both a literal space, in which collaborators can "listen" to a building together before it is built, and a conceptual space, in which participants can form a consensus about how a good building should sound. Patel explains that working with architects in the sound lab has led to improved collaborations.

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196 Raj Patel, interview by the author, 2006.
197 Ibid.
198 Ibid.

> We can relate to architects much better. If we are brought on board at the ideal time, which is if we are brought on board at concept, we can sit with the architect and we can say… this is what you have to work with. They can hear and they can understand it. Then from their first ideas and concepts they are much more willing to work with us when we talk to them about shape and form.[199]

Patel works to bring clients into the sound lab during the early phases of design in order to earn their trust and define a role for Arup Acoustics in discussions about the form of buildings.[200] Patel's accounts about collaboration in the sound lab present design practice is a system of relationships in flux, in which participants are in a continual struggle to define their position.[201] For Patel and his colleagues at Arup, creating a place within this system means negotiating relationships with clients, collaborators and regulators.

In this chapter, I identify and examine the use of simulation by a range of practitioners at Arup to position themselves professionally in design. I will not attempt to explain all possible identities at Arup. Rather, I will try to illustrate the diversity and plasticity of professional roles at Arup through a few salient examples. Practitioners must do two things to define their professional position. First, they must differentiate themselves within the system of design. Second, they must establish spaces of exchange with other design participants. At Arup, a technologically oriented design consultancy, this typically means that their use of simulation must be both technically justifiable and culturally palatable. In this

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[199] From an interview by the author with Raj Patel.
[200] From an interview by the author with Raj Patel.
[201] For an explanation of how professional jurisdiction is negotiated using abstractions see the work of Andrew Abbott, *The System of Professions: An Essay on the Division of Expert Labor.*

chapter, I explain how simulations are used at Arup in this process of professional positioning.

First, I examine accounts from Patel and other acousticians in Arup's New York office about how they use the sound lab to establish a place for themselves in early design discussions about form. They use the sound lab to establish the scientific basis of acoustics and differentiate themselves as scientists, but also to position themselves as co-designers, equal partners to architects, by creating a space of exchange in which issues of form are framed in the language of acoustics.

Second, I examine accounts from engineers at the London offices of Arup. They establish close relationships with architects by adopting an ambivalent stance towards simulation. These engineers are comfortable with using advanced computational simulations to establish their technical legitimacy, their engineering credibility. However, advanced simulations are just a means of confirming their intuition. They embrace sketching as a primary space of exchange with architects. Through sketching, these engineers engage architects on their own terms and position themselves as designers, equivalent to architects. Through sketching they are able to achieve a kind of collaboration that one engineer explains as being democratic.

Third, I draw upon the accounts of practitioners at Arup who have embraced the technical practice of programming simulations as a means of both distinguish themselves and creating a community of knowledge, in which computer regulation defines the space of exchange. By reinventing themselves as toolmakers, these designers have created a new epistemological culture at Arup and new professional relationships with clients, collaborators and regulators.

Practitioners at Arup have found many different ways of positioning themselves in design, through varying levels of engagement with simulation. Each position is technically justifiable and culturally palatable in its own way, within the system of relationships that it is defined.

Scientists and Co-Designers

Wallace Sabine was a professor of physics at Harvard University in 1900, when he derived the Sabine formula for reverberation time. Although Sabine had been working on the physics of sound for years and based his work on a long history of discoveries by other physicists, he condensed his findings into a simple equation in the context of two architectural consulting projects, a lecture hall in the Fog Museum at Harvard and the Boston Symphony Hall. Sabine did not initiate the science of acoustics, but it established a space for the science in design practice. Sabine became the model of the modern acoustical consultant, a new professional identity; he was a scientist working in the realm of design.

In *The Soundscape of Modernity,* Historian Emily Thompson explains that Sabine was given a prominent position in the design of the Boston Symphony Hall by philanthropist Henry Lee Higginson, owner of the Boston Symphony Orchestra. Higginson turned to Sabine to resolve his confusion about how to insure the acoustical quality of his project. Sabine enjoyed a productive collaboration with Boston Symphony Hall's architects, McKim, Mead, and White.[202] However, his presence displaced the traditional role of architects, as acoustical experts in the system of design practice.

Higginson and his architects considered existing means of evaluating architectural acoustics. Since at least the eighteenth century, architects had been using geometric drawings to analyze the propagation of sound in buildings.[203] These drawings could be done on the same paper where plans were laid out; form

[202] Emily Thompson, *The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900-1933.*
[203] Ibid., 18.

was the instrument of control. An alternative approach consisted of reproducing the geometry of traditional auditoriums as a means of replicating the acoustics of great concert halls of the past. But there was little certainty in these methods.

McKim, Mead, and White favored a Greek Theatre plan for Boston Symphony Hall, presumably for aesthetic reasons, but there were no good precedents for it. Thompson writes, "No concert hall had ever been built in the form of a semicircular amphitheatre before, and there was no way to know ahead of time how such a hall would sound."[204]

Sabine's approach veered from architecture's reliance on form as the generator of acoustics. Instead, the Sabine formula takes account of the volume of a space and the absorbency of its construction materials in order to calculate its reverberation time. Sabine reduced the performance of acoustics to a simple expression. However, he did not totally abandon traditions of the past. Sabine used reverberation time primarily as a means of comparing new designs to existing concert halls approved by Higginson. Ultimately, the Boston Symphony Hall was built using a rectangular scheme, proven not necessarily by Sabine, but by history to be the safest choice.

McKim, Mead and White and Sabine worked together to develop the design but Sabine was left to the task of calculating the reverberation time; Sabine retained a scientific role. McKim saw him as a great councilor and advisor, but not a collaborating designer.[205] Sabine moved acoustics into a quantitative zone, apart from the realm of drawing, the realm of the visual, and ultimately the realm of architects. His formula must have been opaque to the architects. Although there were still conversations around drawings to define the form of the Symphony Hall's auditorium, the space of exchange between the architects and Sabine, the scientist, was constrained by one equation. Wallace Sabine created a place for the

[204] Ibid., 15.
[205] Ibid., 17.

scientist in design practice. However, in doing so, he narrowed the discourse on architectural acoustics by framing it exclusively in terms of reverberation time.

Patel characterizes Sabine's discourse as "one dimensional" in order to distance himself from Sabine and the role of the scientist that Sabine represents. For Patel, being a scientist or even an engineer means staying on the fringes of form-making. Today, Patel is challenging the interactions between architects and acousticians that developed in the wake of Sabine's formula in order to take an active role in the determination of form. Through the use of the sound lab, Patel is entreating clients to engage in a new discourse about acoustics and architecture, and to see acousticians in a new way, as co-designers.

> We are kind of a co-designer and collaborator. We become a collaborator. Not the engineer. We don't usurp the role of the designer, but we become a collaborator in the design process.[206]

Patel's distinction between the approach to acoustics characterized by the Sabine formula and his own approach, using the sound lab, recalls Max Weber's distinction between the ethics of the scientist and those of the politician.[207] Weber explains the vocation of science as the pursuit of "clarity."[208] Scientists follow an "ethic of ultimate ends."[209] This means that for the scientist, the ends justify the means. Weber writes, "The believer in an ethic of ultimate ends feels responsible only for seeing to it that the flame of pure intentions is not squelched."[210] Weber contrasts the scientist's "ethic of ultimate ends" with the politician's "ethic of

[206] Raj Patel, interview by the author, 2006.
[207] Max Weber, "Science as a Vocation," in *From Max Weber: Essays in Sociology*, ed. H.H. Gerth and C.Wright Mills (New York: Oxford University Press, 1946), 77-128. and Max Weber, "Politics as a Vocation," in *From Max Weber: Essays in Sociology*, ed. H.H. Gerth and C.Wright Mills (New York: Oxford University Press, 1946), 129-158.
[208] Ibid.
[209] Ibid.
[210] Ibid.

responsibility." For Weber, being a politician means giving priority to the legitimacy of the means over the ends. In their shift from the exclusive use of the Sabine formula, to the pursuit of a consensus in the sound lab, we might say that acousticians have traded the ethics of the scientist for those of the politician. By focusing on a collaborative means of examining architectural acoustics, Patel and his colleagues have created a place for themselves as engaged co-designers rather than objective scientists.

The acousticians at Arup challenge Sabine's quantitative approach to acoustics through their use of the sound lab. They reintroduce form as a variable in acoustics, whereas Sabine only considered volume and material absorbency. They render reverberation time aurally, rather than numerically, bringing it into the realm of common experience. They seek to expand the space of exchange set up by Sabine's formula. Instead of searching for an optimal reverberation time using Sabine's formula, they build a consensus among design participants. Their work has enabled a new space in which the performance of architectural acoustics can be evaluated by technical and non-technical participants in design: a space of virtual acoustical experience.

Through the use sound lab, acousticians at Arup work toward a shared language of objectified, replicable, and controllable acoustic experience. Once a common language is developed, design professionals can identify distinct experiences and their salient characteristics. Experiences can be compared. The ability to perform this kind of shared comparison is the payoff of developing a common language within the sound lab. The result is a more controlled conversation.

This is part of a strategic professional agenda for Arup acousticians. Acousticians are able not only engage in closer collaborations with architects but to claim a new competitive niche within the world of design by presenting the human experience of buildings as a new way in which buildings are accessible by science and technology, and thus a new point of access to design for scientific and technical consultants.

Through new ways of knowing harnessed in simulations like the sound lab, Arup professionals are able to challenge traditional architectural conceptions of human experience like those expressed by Norberg-Shultz and other phenomenologist architects.[211] For Norberg-Shultz, experience is holistic and unpredictable. Patel and his colleagues argue that experience can be compartmentalized and controlled in areas like acoustics, by using the sound lab as an instrument of inquiry. Experience in buildings is simply another realm of professional jurisdiction in which design professionals are now in competition. Acousticians have gained some leverage in this area by balancing their dual identities as scientists and co-designers.

Acousticians at Arup are prone to defining themselves in terms of their interaction with designers. They see a competitive advantage in presenting their roles as accommodating and collaborative rather than visionary. Professionals at Arup alternatively call themselves consultants, collaborators, co-designers, and occasionally designers. Bassuet describes himself as a "room designer" because, he says, of the "holistic way" in which he looks at acoustical spaces.[212] Others, like Patel are wary of usurping the title of "designer." The uncertainty of their identities is most evident in Arup's involvement on architectural competitions. In many of the most selective architectural competitions Arup design consultants are able to participate on more than one design team. I take this to mean that despite Arup's intimate role in design, they are not always considered part of the design team. What emerges from these accounts is the sense that professional relationships at Arup are dynamic. Patel explains it this way:

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211 See Christian Norberg-Schulz, Architecture: Meaning and Place: Selected Essays (New York: Rizzoli International Publications, 1988).

212 Alban Bassuet, interview by the author, 2006.

> It's depending on the project. On some days I am the acoustician in a long line of other consultants and on some projects I'm the client's direct friend and advisor, the person they look to for the right advice for dealing with the issues, and it varies from project to project, purely based on relationship and the time you've known the people or whatever.[213]

Patel's story illustrates the unsettled nature of relationships in design practice. Sometimes, when Patel can find shared ground with clients, he takes on the role of a collaborator. Other times, he is simply a consultant. However, simulations like the sound lab are revealing a contingency, highly specific image of building performance, in which it is difficult to separate technical expertise from design work. The sound lab enables acousticians at Arup to take on an increasing number of close collaborations.

Engineers and Architects

Acousticians at Arup construct productive spaces of exchange with architects and position themselves professionally by using simulations to educate architects in the language of acoustics. Other practitioners at Arup have discovered their own methods of professional positioning. Cecil Balmond is a structural engineer by training and the director of the Advanced Geometry Unit in Arup's London office. He has formed many successful collaborations and earned a prominent place for himself in architectural culture by adopt the language and skills of architects. "Talk in terms of texture and density, instead of torsion and

[213] Raj Patel, interview by the author, 2006.

shear. That way they don't think you are just another nerd," Balmond advises the members of his team.[214] Balmond is a structural engineer who has gained media attention for his collaborations with high profile architects like James Sterling, Rem Koolhaas and Toyo Ito. A recent New York Times article suggests that Balmond's primary talents lie in his skill as a collaborator.[215] The article notes that "beyond making their projects buildable, his solutions open such architects to explore forms they might not have considered before."[216] For Balmond, advanced computer simulations are merely a means of proving his concepts. "The computer is an enabler, but it is never the conceptual model," says Balmond.[217] "Sketches are the means of developing the conceptual model or diagram. The thinking model is made into a spatial model in the computer. The computer reveals the finer grain logic."[218]

Balmond gains credibility from the computer simulations that his group, the Advanced Geometry Unit (AGU), creates for clients and regulators. However, his intimate collaborations with architects and artists are based on his ability to speak the language of architecture and, perhaps just as importantly, his ability to draw. Balmond's collaborators, like Koolhaas, have told him that that he has a special skill in devising abstract models through drawings. Balmond calls his drawings "thinking models" or "concept diagrams."[219] These are models which get the project going and stay with it through development. For Balmond, they are simple diagrams which capture the essence of an building concept.

"When I discovered my talent for abstraction," says Balmond, "I thought it was a unique gift."[220] He realized he could abstract ideas in this way, better than

[214] Cecil Balmond, interview by the author, 2007.
[215] Nicolai Ourousoff, "An Engineering Magician, Then (Presto) He's an Architect."
[216] Ibid.
[217] Cecil Balmond, interview by the author, 2007.
[218] Ibid.
[219] Ibid.
[220] Ibid.

many architects. Later, he learned that this was something that all engineers were taught to do; it was not his gift alone. However, he has learned to combine his ability to abstract design concepts with drawing, out of an interest in working with architects on form making, on how issues of structure meet issues of aesthetics. Balmond argues that these interests have put him in a unique position at Arup; he sees himself as a designer.

Balmond and Patel describe their relationships with architects in very different ways. For Patel, advanced simulations are at the center of his work; the sound lab bridges between the technical means of acousticians and the needs of architects. Balmond prefers working on architects' terms. His use of advanced simulations is often merely supportive. Balmond uses his collaboration with architect Rem Koolhaas on the CCTV project in Beijing as an example of how advanced simulations can be used in a purely "technocratic way."[221] The project required "a ferocious amount of computation," says Balmond.[222] Koolhaas had to wait six months while Balmond and his engineers did the calculations on their own. It was an example of the use of simulation as "muscle."[223]

[221] Ibid.
[222] Ibid.
[223] Ibid.

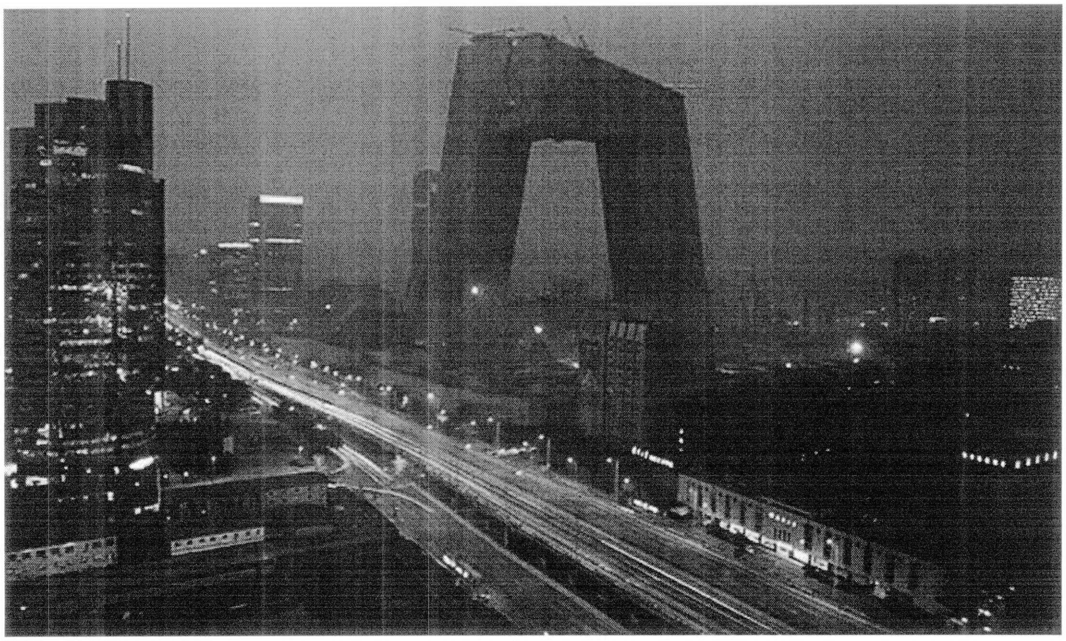

Figure 24. CCTV Television Headquarters in Beijing. Nicolai Ouroussoff, "In Changing Face of Beijing, a Look at the New China," *New York Times*, July 13, 2008, Design Section.

Balmond finds drawing to be a useful way of intervening in the process of design. He is not alone in his preference for drawing as a space of exchange with architects. Bob Lang, the structural engineer, likewise says that sketching is an important part of developing a good rapport with architects. "You need to understand what they want to achieve and interpret it."[224] Drawing can be seen as a kind of simple simulation. It allows engineers like Balmond and Lang to reconstruct architects' designs using alternative media, the media of their own hands, eyes, and minds. The notion that drawing is a form of simulation is subtlety suggested in Balmond's characterization of his drawings as "abstract models." Balmond's drawings interpret the design intent that architects bring to their collaborations and make room for structural concerns. Sometimes his work blurs the boundaries between the concerns of engineering and the concerns of architecture. In 2002, Balmond collaborated with Toyoto Ito on the Serpentine

[224] Bob Lang, interview by the author, 2007.

Pavilion in Hyde Park, London. Balmond made extensive use of his engineering knowledge of structures and computation to work on the project, but his goals were aesthetic, architectural. "I thought about the rhythm of the lines intersecting. It was a rectangular container but we wanted to undermine its containment factor. I thought that the intersection of lines would create such a puzzle for your eye that your eye would travel through the cell. It's an aesthetic game. That gives you the pleasure to the eye."[225] Balmond's attempts to transcend the traditional division between architecture and engineering has met resistance from the culture of architecture. One New York Times architecture critic reproaches Balmond for trying to push beyond the boundaries of engineering. "Mr. Balmond has decided that the title of engineer is not enough."[226] Balmond's stance is that he focuses on building, rather than adhering to traditional divisions between engineering and architecture.

Balmond gains technical leverage in the world of architects by using advanced simulations, but he challenges the perceived distinction between architects and engineers through his ability to engage projects with a combination of an architect's skill with drawing and an engineer's mind for abstract thinking. Balmond has gained notoriety, positive and negative by moving between the worlds of engineering and architecture. As in the case of Patel, professional labels do not adhere.

[225] Cecil Balmond, interview by the author, 2007.
[226] Nicolai Oursousoff, "An Engineering Magician, Then (Presto) He's an Architect."

Figure 25. Serpentine Pavilion. Image courtesy of Arup.

Balmond is one of many practitioners at Arup who leverage their ability to draw in collaborations with architects. He explains that abstraction through diagrammatic drawing is something that all engineers are taught to do. Graham Dodd is a British mechanical engineer who relies almost exclusively on sketches and hand calculations.[227] He works for the Arup Facade Group in London and claims that his expertise is in understanding material properties and assemblies. Dodd is satisfied using simply his hands to work out technical facade details. "I haven't used CAD in 13-14 years," he says proudly.[228]

Dodd shows me a typical report for the Heathrow East Terminal project, in which most of the drawings are done by hand. "We are working in a niche where we do a lot of hand sketches."[229] He says that sketches allow you to share a

[227] Graham Dodd, interview by author, 2007.
[228] Ibid.
[229] Ibid.

lot of ideas very quickly and to integrate a lot of different perspectives. As a space of exchange, Dodd makes the point that sketching is more democratic. "Sketches are way faster and more democratic. When we meet with the architects, we can do these sketches together, live."[230] Dodd explains that sketching is so much more involving of the team. "It reflects the fact that this is not a finished design. People know we are still exploring options. They don't turn off their critical faculties the way they do with some computer drawings."[231]

Although Dodd is able to develop a rapport with architects by adopting the traditional architectural medium of drawing, he attributes the overall success of facade design at Arup to the technical prowess of its engineers and the comparative "deskilling of architects."[232] From his perspective, architects have moved away from expertise in materials and the technical aspects of building. This is coupled with new technical demands on facades, which are not being met by architects. Some of these demands have come from legislation, explains Dodd; standards are being pushed up for energy efficiency. But architects like Norman Foster and Richard Rogers are also just envisioning more complex facades, without an understanding of how to design them. Dodd says that this trend is part of "post-modern" architecture, a movement that he says has brought on an increasing interest in complex shapes. Architects have placed new, more technical demands on facades, especially glass facades, desiring to use them for structural purposes and for passive environmental control.

According to Dodd, contemporary façade designs have necessitated a new, rigorous, technical approach to design. But he does not equate this technical approach with computers. Dodd says that Arup's success in the area of facade design was not enabled by calculation. Dodd acknowledges that some façade

[230] Ibid.
[231] Ibid.
[232] Ibid.

designers at Arup are using "heavy modeling" to analyze these facades.[233] He concedes that numerical analysis has supported new forms. But for day-to-day design, says Dodd, simple rules, and experiments with full size mockups are enough to design these systems.[234] "I don't use my computer for much more than e-mail."[235]

Dodd, Lang, and Balmond acknowledge the usefulness of simulations, but are wary of their potential to get in the way of collaboration. They have created positions for themselves in design practice by bringing their technical knowledge to drawing, as a space of exchange with architects. Each asserts that architects have relinquished their traditional technical knowledge about buildings. This is a widespread belief. To compensate, some practitioners at Arup demonstrate their technical knowledge through drawing, others rely on advanced simulations to highlight areas where architect-designed schemes are technically weak.

Mikkel Kragh, like many of his colleagues, asserts that "the new technology of building facades is not something that an architect can master."[236] Kragh works from a belief that "there used to be a master builder, but that no longer is the case."[237] However, he focuses almost exclusively on the use of advanced simulations to leverage his technical know-how. He works on facade design in London, but not in the same group as Dodd. Kragh started work with the Arup Facades group in 2000, but now works with Arup's Environmental Physics Group. Kragh is trained as both a civil and a structural engineer. He holds a PhD in building physics from the University of Denmark. He has an interest in understanding how current simulations tools can be used more effectively; he

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[233] Ibid.
[234] According to Dodd, CFD analysis is especially useful for curved glass facades like the double-paned model Dodd points out to me in his studio. Dodd says that when the air inside this curved design heats up and expands, "strange things happen," which could break the glass.
[235] Graham Dodd, interview by author, 2007.
[236] Mikkel Kragh, interview by the author, 2007.
[237] Ibid.

wants to "understand their limits."[238] Kragh and Dodd are both working on facade design, but in very different contexts.

The Environmental Physics Group does about 80% of its work for other groups within Arup, as a means of enhancing the services provided by typical Arup building teams. Only 20% of the group's time is spent with external clients, like architects. Kragh acts primarily as an internal consultant. He does not stress the importance of drawing; he uses more technical language to collaborate with other engineers and scientists at Arup. This differentiates the context of Kragh's work from that of Dodd. Dodd feels that he must define his professional position through drawing. When Kragh does work with architects, he describes it as "taking them on a tour" of technical issues using simulations.[239] Kragh does not share the intimate collaborations that Dodd has with architects.

Dodd, Lang, Balmond, and Patel are part of a tradition of collaboration at Arup. Ove Arup built his reputation on close relationships with architects like Lubetkin, Utzon, Rogers, and Piano. Although they continue to believe in the importance of a close collaborations with architects, these practitioners have new ways of negotiating their relationships. For example, in Dodd's work we can see a continuation of the traditional architect-engineer relationship, but we can also see new boundaries drawn, new areas in which engineers, not architects are the experts. Although Dodd works in facade design, an area which is traditionally a domain of architecture, his approach is specialized and highly technical, his methods of practice are engineering methods. He does not take up Balmond's interest in the aesthetic qualities of buildings, the qualities that architects are most likely to address. Kragh works more closely with simulations, but he sacrifices the close collaborative relationships with architects that some of his colleagues have.

[238] Mikkel Kragh, interview by author, 2007. "Therm" and "Window" are two pieces of software used in Kragh's group, but produced at Lawrence Berkley Lab.
[239] Ibid.

Toolmakers

> "Writing programmes for a computer is rather like learning to speak a foreign language... A few stumbling sentences are permissible, but it is entirely another matter when it comes to attempting a novel. The conception, production and 'de-bugging' of a complex programme is a job for a fluent 'linguist' - not a civil engineer."[240]

At the time of Arup's 1963 "Symposium on the Use of Computers," most technically oriented design practitioners at the firm conducted their analysis of design by hand. For these practitioners, programming was an opaque means of describing the world. It appeared to be a foreign and tedious practice. They assumed that making good software would employ a new kind of expertise, not one appropriate for design practitioners.

Since then, programming has become a primary means of working for many design practitioners at Arup. In this section, I will examine the stories of practitioners who have made programming and the development of software their means of participating in design. When I first started to look into programming practices at Arup, I assumed the firm was hiring computer scientists to write software. In an early proposal to Arup, I explained that I was interested in studying whether programmers were becoming designers. I was immediately corrected by the director of the American offices, Mahadev Raman, a mechanical engineer by training. "This is wrong. Software engineers aren't becoming designers, it's the other way around!"[241] Contrary to what I expected, and what some Arup practitioners expected in 1963, software development at Arup is done

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[240] *Arup Newsletter* 17, 5.

[241] Mahadev Raman, interview by the author, 2006.

primarily by people with backgrounds in design. These design practitioners have become design toolmakers. As members of the culture of design, they are able to address the unique conditions and demands of design. Many of them are self taught programmers. They have created new roles for themselves by embracing the language of the computer as a means of extending the discourse of design.

> But the use of a computer for small problems is another matter. In this case it is better for the engineer to write small programmes. And the distinction between small and large programmes is dependent on the experience of the engineer.[242]

By the time of the Symposium, some Arup practitioners had already caught on to the idea that engineers could create their own small programs to solve project based problems. Today, many practitioners at Arup do develop their own programs. "You get lots of little pockets of development," says Alec Milton, director of Oasys, a group at Arup's focused on the development of general use software packages.[243] "Programming is becoming easier because it's taught in the universities," explains Milton.[244] Although Oasys turns out its own software, it also facilitates the augmentation of software by regular practitioners at Arup, through methods like script writing.

By embracing programming at Arup, individuals become part of a new community of practice. Programming is a way of building upon what has been done before. It is a means of fitting into a society of toolmakers. In order to encourage scripting writing, Milton and his team have developed a common interface, enabling practitioners to automate existing applications like GSA,

[242] *Arup Newsletter* 17, 5.
[243] Alec Milton, interview by the author, May 2007.
[244] Ibid.

Arup's homebrewed general structural analysis program, produced by Oasys. "People see an opportunity to improve something. Sometimes those bits of development become major applications," says Milton.[245]

Fablon is one of the many simulations that was written by design practitioners at Arup for specific projects, but is now accessible by anyone with a copy of GSA. Fablon went through several phases of development on projects before it became part of Arup's standard structural engineering package. It passed through the hands of many individuals at Arup. Fablon works on the principle of "dynamic relaxation," first explored at Arup by Alistair Day in the 1970s. Day was an Arup engineer and an academic. Dynamic relaxation is general method of non-linear analysis, which relies on an iterative approach to resolve the relationships among a number of independently defined elements. Through Fablon, dynamic relaxation was adopted at Arup as a technique for form-finding in cable and fabric structures.

Day first explored the possibilities of dynamic relaxation on punch card computers. Fablon was written in the computer language "C" for use on a Sun Spark station.[246] This version was intended to be used throughout the Arup office for fabric, cable and mast structures. One of the earliest applications of Fablon was the Schlumberger fabric structure in Cambridge, UK, designed in conjunction with architect Michael Hopkins and completed in 1984. Brian Foster, a fabric expert at Arup, worked on Schlumberger, but didn't operate Fablon. Foster didn't use computers at all. He was the designer; his collaborator was "the software guy."[247] Schlumberger needed both of them.

Tristran Simmonds, a young engineer who joined Arup in 1995, converted Fablon for use on Windows machines. Simmonds works in the London offices of

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[245] Ibid.
[246] Tristram Carfrae, now one of the leading structural engineers at Arup, started out working with Brian Foster and writing code for Fablon.
[247] Tristran Simmonds, interview by the author, 2007.

Arup with the Advanced Geometry Unit. In 1998, Simmonds rewrote Fablon over the course of three weeks for use on a project in Tokyo, Jusco. There was no architect on the project. The majority of the building was designed by a contractor. Arup was hired to resolve the fabric roof. When Simmonds started on the job, Hitoshi Yonamine was the lead Arup engineer, stationed in Tokyo. According to Simmonds, Yonamine had only a crude physical model, made of balsa wood and tights. Simmonds appropriated the algorithm developed by Alistair Day and tested by Brian Foster on Schlumberger.

Most recently, Fablon has been integrated into the general use analysis program produced out of Oasys. However, individuals are still bending it to their own needs. Other engineers at Arup, like Sarah Kaethner, have also taken up Fablon on specific projects. Many times, practitioners adjust and update the Fablon code in order to meet the requirements of clients. Chris Kaethner, the husband of Sarah and one of the members of Oasys, describes this as practitioners "bending" and "tuning" the simulation to satisfy their needs.[248] "Some of them get it to sing," explains Kaethner, but every practitioner that has used Fablon has contributed to the culture of programming at Arup.[249] One of the consistent attitudes towards simulation at Arup has been that individuals should be given space and support to develop their own tools, says Kaethner.[250] If someone has an idea, the computing groups will help them carry through on that idea. If the idea

[248] Chris Kaethner, interview by the author, 2007.
[249] Ibid.
[250] Ibid. Early on in the history of the Lighting Design Group, Andrew Sedgwick used Fortran to code some of his own programs for daylight analysis on UNIX, sun workstations. He produced early renderings using finite element methods directed at surfaces. In the mid-nineties, he started to incorporate ray-tracing in addition to finite element techniques. Eventually Radiance became the principle analytical tool for lighting analysis at Arup. Modification and adjustment through scripting has been adopted in areas like lighting design, where Arup does not typically develop the base simulations anymore. Andrew Sedgwick explains that although Arup lighting designers no longer write their own software, they frequently write scripts that extend or automate commercial simulations like Radiance. According to Sedgwick, scripting has helped his team to break the cycle of hypothesis, analysis, and discussion that has limited working relationships between lighting designers and architects.

is generalizable, then sometimes it is made into an application and disseminated throughout the firm.

In the original version of Fablon, developed under the supervision of Alistair Day, the program was written tersely in C and took input from text files. Each text file consisted of a list of coordinates for nodes and connecting elements (bars and cables) and parameters for those elements. Fablon was difficult to use for design. Currently, Simmonds is working on bringing simulations like Fablon into the early phases of design, by making them more visual and interactive. Eventually, he hopes that such simulations will be accessible from inside ubiquitous modeling platforms like AutoCAD.

> We tend to be more hands on with projects. We use automation techniques to go back and forth, adding and subtracting elements until the design works. [It is an] iterative kind of optimization. It allows you to deal with complex forms. You get rid of the bottle-neck of analysis. Previously, it might take you a month to run the analysis, now there is a potential to do some analysis in real time or close to it.[251]

In the Advanced Geometry Group, of which Simmonds is a part, projects are emphatically collaborative. Working with simulations like Fablon not only extend the work of his predecessors at Arup, like Alistair Day and Brian Foster; Fablon allows Simmonds to collaborate more creatively and in new ways. "This allows the designer to go forward," says Simmonds. "It offers new freedom to be expressive, for both architects and artists."[252]

In the last chapter, I examined how simulations function as spaces of

[251] Tristran Simmonds, interview by the author, 2007.
[252] Ibid.

exchange that enable new discourses about form. Spaces of exchange are also the context in which professional identities are constructed. For example, Simmonds has created a place for himself through his work on Fablon. Simmonds and other programmers at Arup have become catalysts for a new exploration of form. But oftentimes, the programmers do not introduce themselves as designers. Simmonds sees his role as empowering. When he talks about a new freedom for designers "to go forward" and "to be expressive," you get the sense that he is not talking about himself. Simmonds contributes through the tools he makes for designers. When Simmonds used Fablon to help the artist Anish Kapoor design Marsyas, a grandiose stretched fabric structure of for the Tate Modern in London, Kapoor, was Simmonds a designer or a toolmaker or both?

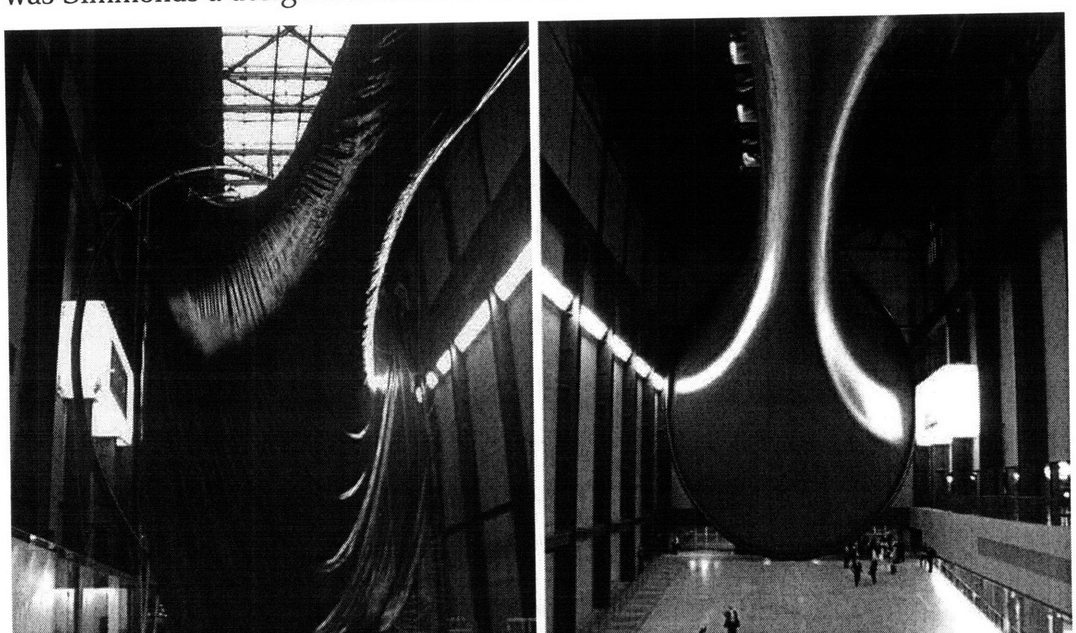

Figure 26. Marsyas Fabric Sculpture. Image courtesy of Arup.

Only recently has Fablon attracted enough users to make it worth broad support by Oasys. When Simmonds revived the code for Windows, he was the only user. There was no money and no support to develop Fablon because there was no demand. Now Thomas Li, a programmer at Oasys, has taken on the task of distributing Fablon more widely, by integrating it to GSA. Li wrote a wrapper that allows Fablon to communicate with GSA. This process has taken four years and has resulted in a more limited version of the simulation. "Bits of the original Fablon have been taken out and the whole program has been dumbed down," laments Simmonds, even though he concedes that most of the elements taken out were not likely to be used.[253] The primary benefit of Li's work is that Fablon has attained a visual graphic interface, through its integration with GSA. You no longer have to be a "super-specialist," to use it.[254]

Sometimes, the difficulty of programming problems defies the abilities of the typical practitioner at Arup. "It is a professional job to produce a useable programme and the larger and more complex the job, the more vital is professional help."[255] Arup has in-house software development groups like Oasys and the Advanced Technology Group that can aid project-based practitioners in developing needed software. One of the "core values" of Arup is the capability to solve any problem for the customer, no matter how difficult, says Richard Sturt, a member of the Advanced Technology Group who works out of the Birmingham, UK.[256] "I only get involved when the problems are really difficult, when there are no existing resources to solve the problem within Arup."[257] Sturt had little computational training when he entered Arup, after studying general engineering at Cambridge University. Over the course of twenty years at Arup, he turned into

[253] Tristran Simmonds, interview by the author, 2007.
[254] Ibid.
[255] *Arup Newsletter* 17, 6.
[256] Richard Sturt, interview by the author, 2007.
[257] Ibid.

a programmer.

Oasys performs some of the same tasks as Sturt. For instance, Alec Milton encountered a practitioner who was painstakingly trying to work out the optimum seat racking on a stadium so that he could pack in as many people as possible, while allowing visibility of the field for all. Milton first learned about the practitioner's method by asking questions. "How do you work this out? What's your calculation?"[258] Within a few days, they had built a rudimentary piece of software together. "You cold put in the basic parameters and it would optimize that curve for him, showing every single tread and so on."[259]

When the expertise to do this programming is not on hand in the project team, practitioners like Sturt, Kaethner, and Milton step in to help. They create new software through creative discussions with project teams. Converting design thinking into broadly applicable software is their professional role; they are toolmakers. Sturt sees this as "backroom" work.[260] Kaethner has an empowered view of his role. He says that his work on graphics, interfaces and manipulability can encourage more interrogation of what's behind the software and an increased sense of responsibility on the part of users to filter the results.

Sturt and Kaethner have backgrounds in engineering.[261] They did not chose to become full time programmers, but this has become their role in design. Milton, was trained as a product designer. "I'm more qualified to design a washing machine, than I am to do anything with a building" says Milton.[262] Milton learned to program on his own. "I think a lot of people work that way.

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258 Alec Milton, interview by the author, 2007.
259 Ibid.
260 Richard Sturt, interview by the author, 2007.
261 Kaethner was trained as a civil engineer at Liverpool University. At university, he had limited engagement with computers. He used punch cards to run several structural analysis programs on an old HP computer.
262 Computers were part of Milton's education to a very small extent. His course required only a little bit of programming, but he had a "particular interest in computers," and had already learned to program on his own.

I'm not unique in that respect."[263] In the last 5 years, Oasys has become financially independent. The group earns money by selling software products both internally and externally. In a financial sense, Arup is now a customer for Oasys. However, decisions at Oasys are still directed by discussions within Arup and the work of Oasys is still as much about developing a community at Arup as it is about independent economic success. For example, explains Milton, the transition from DOS to Windows, Kaethner says, was largely about preserving relationships within Arup. "I had good relationships that I didn't want to give up. They had confidence in what we were doing. I didn't want to lose that."[264]

In house software development at Oasys offers Arup an opportunity to develop new theories and to extend existing ones; a platform like GSA accommodates add-ons and refinements easily.[265] This also allows for some degree of quality control. In addition, in house software development is useful in a global organization, because it offers the potential for commonality, a consistent shared platform. Given Arup's diverse network of offices, explains Milton, it would be impossible to have this commonality without a in-house platform.[266] In the US they would be using one software, in London another, in Australia, yet another. These choices would be driven by individual preferences but also by clients, regulations, and other local considerations.

Building good software is often about the relationships the software

[263] Alec Milton, interview by the author, May 2007.
[264] Ibid.
[265] Milton explains that although Oasys sells it software externally, they primarily develop software for Arup internally, then sell it. It doesn't often work the other way around. The development of software is usually driven by some demand that's occurred inside the firm. For instance, in tunnel settlement work, on the cross rail project, there was a need to refine the software to provide damage assessment to buildings as a result of tunnel excavation. The project team wants this and is contributing in part towards the development. The rest of the cost is met through a general charter in the firm for developing that piece of software. The project team is devoting both time and financial resources to improving the software. As a result, it gets put at the top of the agenda. Otherwise, software projects are organized by the skills networks. These are experts in the firm who drive these things and decide what's best for the firm.
[266] Alec Milton, interview by the author, 2007.

enables. "Simulations broaden the perspective of individuals," explains Tony Sheehan, the director of knowledge management at Arup.[267] "They reassure you. They say someone has done this before." [268] One of the things that makes Arup's software so good, offers Kaethner, is the level of support that Oasys employees put behind it. Even though there are only a handful of people in the London office of Oasys, they spend a considerable amount of time helping project teams to realize specific goals. The work of Oasys enables Arup's broader culture of programming.

In *Making Sense of Life*, Evelyn Fox Keller suggests that experts can be defined by their methods of representation.[269] Keller studies scientific practices in biology, but her framework can be used to understand how design practitioners at Arup address form, knowledge, and identity though their standards of representation. For Keller, the temporal, disciplinary, and culturally specific needs that must be satisfied by a representation, are the characteristics that define an "epistemological culture."[270] These needs may be for prediction, control or simply narrative coherence. They may be cognitive, instrumental, social, or psychological needs. The aim of any representation is usually to satisfy many needs at once. Programming links designers at Arup across disciplinary boundaries, through generations and around the world. Programming is a facet of professional identity.

Code has become another means by which practitioners at Arup can position themselves within design. Writing software has joined practices like writing of technical papers as a culturally acceptable means of contributing knowledge at Arup. Using, augmenting, and developing simulations is a way of

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[267] Tony Sheehan, interview by the author, 2007.
[268] Ibid.
[269] Evelyn Keller, *Making Sense of Life. Explaining Biological Development with Models Metaphors and Machines* (Cambridge: Harvard University Press: 2002).
[270] Ibid.

being part of a new culture of design at Arup and a means of reaching outside of the firm to clients in new ways.

Programming simulations can make one part of a community. Taking part in this process is a new way to find a niche in design practice at Arup. It ties people in with theories from the past and promises that their own contributions will be distributed to others in the future. However, Kaether is wary that becoming too reliant on the chain of knowledge in simulations can become a form of dependence. He sees this as one of the main problems of Oasys. How can Arup overcome the problems of increasing dependence on software? Kaethner sees a willingness, especially on the part of younger designers, to ignore what's behind the software, to deal with building physics directly. "In days gone by there was more vigilance."[271] Similarly, Bob Lang fears that young engineers rely too much on the computer. He says that there is a dangerous assumption that if you can build it in the computer, then you can build it on site. Today, there is a paradox. As models get bigger and more sophisticated, there is an increasing need to understand what happens inside them in order to interpret them accurately.

These comments recall Sherry Turkle's distinction between two kinds of "transparency" in technological cultures.[272] Modernist transparency is the notion that users can and should access to the inner workings of a technology. This is the kind of relationship with simulation that Lang and Kaether want for design practitioners. "A good project engineer will know what to expect from a simulation," says Kaethner.[273] Turkle contrasts this with an opposing, post-modern meaning of the term, the notion that something is transparent if you can use it without knowing how it works. Post-modern transparency allows the user to navigate the surface of a system, without ever having to access its underlying

[271] Kaethner, interview with the author, 2007.
[272] See Sherry Turkle, *Life on the Screen: Identity in the Age of the Internet.*
[273] Kaethner, interview with the author, 2007.

mechanics. This is the understanding of technology that Patel offers to architects in the sound lab. For Patel, a good simulation is immersive and equalizing. It allows participants in the sound lab to come to a consensus because they all experience the same transparent understanding of sound. In contrast, Kaethner argues that good simulations, their graphics, interfaces and manipulability, should encourage more interrogation of what's behind the software.

Practitioners at Arup favor different perspectives on simulation. Patel is able to build consensus among clients through simulations. Balmond uses simulations to support his intuitive work in collaborations, but favors simpler more intimate collaborations through sketching. Dodd turns away from simulations completely in order to engage people more fully. Simmonds engages simulations in order to empower his clients and collaborators. Sturt, Kaether, and Milton translate the knowledge of a few engineers into widely accessible simulations. Each of these practitioners has found new ways of being creative and establishing an identity in Arup's culture of simulation.

Pragmatists and Academics

In the practice of developing new simulations, building good relationships with clients and collaborators can be more important than chasing after an ideal of truth. Sturt contrasts two approaches to the development of simulations. One approach, which he terms "pragmatic," is focused on the needs of users and how they are going to use the simulation.[274] For example, if users simply want to satisfy local building regulations, then official tables describing what happens to concrete at a certain temperature might be hardwired into the simulation. An

[274] Richard Sturt, interview by the author, 2007.

alternative approach is more "academic" says Sturt.[275] The academic approach is to represent the intrinsic properties of construction materials used in a design, rather than relying on the simplifications defined in the regulation. Take the example of structural analysis. The academic approach would be to model the millions of minute elements, at the scale where researchers believe the important physical dynamics are occurring. The more practical approach would be to simulate the broad overall effect; the empirical results of macroscopic tension and shear tests might be fed directly into a simulation. We mix and match these approaches, says Sturt.

Sturt's distinction between the pragmatic and the academic approach reveals that prescriptive and performance-based knowledge are both used in the practice of simulation. The pragmatic approach might make good use of prescriptive knowledge. Meanwhile, the academic approach necessitates more specificity; the academic approach might adopt a performance-based conception of knowledge. But this is not necessarily the case. I understand Sturt's distinction to be more about identity, than the use of particular techniques. Sturt's account recalls Max Weber's discussion of professional identity in his writings on science and politics as vocations, which I introduced at the beginning of this chapter. When practitioners at Arup model the millions of minute elements in a structure, they are following an "ethic of ultimate ends." When they forgo the tedious practice of modeling and simulate the expected effect, they are following an ethic of responsibility.

The close-fitting analogy between Sturt's approaches and Weber's vocations suggests that switching between approaches to design can also mean switching between professional identities. From one project to the next, professionals at Arup can be seen to move between conflicting conceptions of

[275] Ibid.

identity. Sometimes they play the academic. Like Weber's scientist, they are looking for absolute truth. Other times, they take on the role of the pragmatist and simply follow the regulation. In these cases, like Weber's politician, they are simply interested in the legitimacy of the means. Sturt says, "the right approach comes out of creative conversations you have with those on a project team."[276] Professional identity at Arup is expressed and negotiated in the context of collaborative design projects. Contested conceptions of identity, like conceptions of form and design knowledge, are reconciled in a shared space of exchange.

Conclusion

Design practitioners at Arup define their identities within a system of professional relationships. Increasingly, information technologies for simulation frame of these relationships and are the objects of intensely felt relationships themselves. In previous chapters, I examined at how new conceptions of knowledge and form emerge in spaces of exchange shaped by simulations. New identities also emerge in these spaces. Depending on the exchange, professionals may take on different roles and identities. In this chapter, I have used case studies from a number of disciplines to explore how relationships and identities are negotiated in the context of new spaces of exchange developing around information technologies for simulation.

In order to define a position for themselves within the system of design practice, practitioners must do two things. They must differentiate themselves and they must establish spaces of exchange with other participants in design. In the cases examined in this chapter, I have found that simulations play significant but varied roles in this process of professional positioning.

[276] Richard Sturt, interview by the author, 2007.

First, I examined accounts from Raj Patel and his colleagues in the Acoustics Group at Arup's New York office. They use their immersive acoustical simulator, the sound lab, as a means of establishing a position for themselves in the early stages of design, where they can have an input on issues of shape and form. Acousticians at Arup are able to engage in closer collaborations with architects and to claim a new competitive niche within the world of design by presenting the acoustical experience of buildings as a new way in which buildings are accessible by science and technology, and thus a new point of access to design for scientific and technical consultants. Experience in buildings has become another realm of professional jurisdiction in which design professionals are now in competition. Although acousticians gain legitimacy through their status as scientists, they increasingly position themselves as co-designers. Patel makes a distinction between the co-designer's collaborative, consensus building approach to acoustics, enabled by the sound lab and an older means of acoustical simulation, the scientist's approach, best characterized by efforts to optimize reverberation time using the Sabine formula. This distinction, between consensus building and optimization recalls Max Weber's explanation of the conflicting ethics of the politician and the scientist. In shifting acoustics from a practice of optimization to the pursuit of a consensus we might say that acousticians at Arup have traded the ethics of the scientist for those of the politician in an effort to create a new, more engaged identity for themselves in design practice.

Second, I examined the accounts of engineers at the London offices of Arup. They establish close relationships with architects by adopting an ambivalent attitude towards simulation. Advanced computational simulations establish their technical legitimacy, but sketching is the primary space of exchange in which they interact with architects. Through sketching, these engineers engage architects on their own terms and position themselves as designers in their own right.

Third, I drew upon the accounts of practitioners at Arup from different backgrounds who have embraced the technical practice of programming simulations as a means of both distinguish themselves from other practitioners and creating a new epistemological culture.

Simulations link professionals to a history of work at Arup across projects, generations, disciplinary boundaries and around the world. To a certain extent, making and sharing simulations has replaced a culture of exchanging technical papers within Arup. Those who augment or program their own simulations find that programming is a way of connecting to others by building upon what has been done before. Every designer that has a part in programming a simulation contributes to a shared pool of knowledge. Programming is also a means of differentiating one's self. Designers "bend" and "tune" simulations to satisfy their own and interests. Meanwhile, larger scale in house software development offers Arup practitioners around the world the potential for commonality, a consistent shared platform. Building software can also mean building relationships. Developing simulations is about developing a community at Arup.

Contrary to what Arup engineers expected at the adoption of computers, software development at Arup is done primarily by people with backgrounds in design. Designers are able to address the unique conditions and demands of design in code. By reinventing themselves as toolmakers, many practitioners have created a new culture of knowledge at Arup and new positions as programming consultants for engineers, architects, artists and other design practitioners outside the firm.

When simulations are brought to the center by Arup practitioners, they can bridge between the means of science and engineering and the needs of clients. Sometimes this just means that technical practitioners at Arup are taking architects "on a tour" of technical issues using simulations. However, some professionals at Arup see simulations as a new shared space of exchange, in which design decisions can be made through consensus. For some professionals, simulations can't replace sketching as a democratic space of design. However, in areas of design which focus on the experience of buildings, like lighting, acoustics, and fire safety, simulations enable a discussion of experience that is not possible through sketches. These simulations create a shared virtual space of collaboration in which technical professionals at Arup can work closely with design participants.

Through relatively few examples, these stories illustrate the diversity and dynamism of professional identities at Arup. Practitioners at Arup have found many different ways of positioning themselves in design, through varying levels of engagement with simulation. Each position is technically justifiable and culturally palatable in its own way, within the system of relationships that it is defined. Sherry Turkle writes about circumstances in which technology is adopted by individuals not for what it does for them, but for how it makes them feel.[277] Strategic practitioners at Arup certainly adhere to this, but they also weigh the affect of simulations on their collaborations. They often adopt or eschew simulations for how these technologies make their clients feel.

[277] Sherry Turkle, et. al., *Information Technologies and Professional Identity: A Comparitive Study of the Effects of Virtuality*. Report to the National Science Foundation. MIT, 2005.

CHAPTER 4 INTERPRETATIONS

In this chapter I reflect on my studies at Arup through two theoretical frameworks for thinking about simulation, as narrative and as theatre. First, I discuss how simulation might be thought of as part of *professional narratives* which practitioners use to make sense of their work. Professionals at Arup use *technical narratives* to describe simulations. They use *analytical narratives* to describe design problems. They develop *methodological narratives* to explain the way they work. Finally, they turn to *reflective narratives* to consider the effect of their work and their professional role in design. Through working relationships with people and technologies, professionals develop these narratives and weigh them against one another. Second, I reflect on an implicit metaphor in use at Arup, that simulation is a kind of theatre. I find that by probing this metaphor, we can understand the practice of simulation more deeply. The production of building performance, the design of analytical scenarios, and the representation of human experience in buildings, all done through simulation, are a balance between immersive and critical ways of engaging audiences. Creating a valid simulation at Arup, like creating a successful theatrical performance, is all about engaging your audience in the right way.

Design as Narrative

One way of reflecting upon the fluctuating conceptions of design at Arup is as a set of narratives in dialog. Arup is already beginning to see itself in this way. "We are moving away from structured databases and towards stories," says Tony Sheehan, Director of the Knowledge Management Group at Arup.[278] "There is an acknowledgement that people like to work with stories. Simulations, to an extent, build upon stories that people already know about how buildings work and how design works."[279] These narratives may be seen as structuring the very accounts about simulation that I have collected at Arup, the empirical basis of my study.

Design narratives are the primary means by which professionals explain simulations to themselves, regulators, collaborators and clients. As such, they the offer a means of tracking the fluctuating culture of simulation. One method of describing a culture is by accounting for the narrative models that it "makes available" for interpreting life events.[280] Here, I describe the culture of simulation at Arup through an examination of the narrative models that it makes available for working out designs. "Stories happen to people who know how to tell them," writes Henry James. I take this to mean that simulation can only be done by someone who knows how the narrate it. Conversely, knowing how to produce a professional narrative about design at Arup increasingly means using the discourse of simulation.

Psychologist Jerome Bruner acknowledges that the study of thought processes has much to gain from fields of study that take narrative itself as their object of study. Bruner examines autobiographical narratives for psychological inroads to understanding self perception. He turns to the Russian Formalists for help in dissecting narratives. The Russians decompose narratives into three parts: fibula (theme), sjuzet (discourse), and forma (genre). My decomposition of

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278 Tony Sheehan, interview by the author, 2007.
279 Ibid.
280 Jerome Bruner, "Life as Narrative," in *Social Research* 54, 1 (Spring 1987).

professional narratives at Arup follows the tripartite structure of Russian formalism quite closely. Firstly, I am interested in a series of three themes that professional narratives in design invariably deal with. I call these themes conceptions of design. The conceptions that I'm studying are form, knowledge, and identity. Secondly, the terms of discourse that are used in professional narratives are an important part of my study. Discourses determine the space of shared meanings among collaborators, what Peter Galison calls the trading zone. Lastly, I am interested in the genres used in professional narratives. In my work, these genres are best understood as layers of interpretation: technical, analytical, methodological, reflective, cultural. I have found that it is the discourse of narratives which has substantially changed along with new information technologies for simulation. The themes and genres for constructing professional narratives at Arup have largely stayed the same over the past century.

Although themes are meant to be timeless in Russian formalism, the themes that I have chosen are predominantly themes of twentieth and twenty-first century design. This is the era in which Arup developed. Each of these themes is invoked in design narratives. The theme of 'form' addresses the properties of designs. The discourse around form identifies a range of designs acceptable in the culture of building simulation at Arup. The theme of 'knowledge' addresses the ways that designers have of describing designs. The discourse around knowledge articulates acceptable ways of developing, maintaining and communicating knowledge. The theme of 'identity' gives definition to the people who do design. It's discourse identifies roles and relationships that are available for one working in a culture of simulation.

Discourses are the shared spaces in which design participants negotiate various themes of design: the significance of form, what passes for knowledge, and acceptable the roles and relationships among design professionals. Discourses have changed significantly along with simulations, while traditional themes and genres have remained more or less the same.

The discourses around early efforts at Arup to apply computers to design were focused on the mechanical analysis of building performance: lighting designers focused on illuminance levels, acousticians focused on the reverberation time of sound, and fire safety engineers worried about structural failure. Through simulation, Arup professionals are turning the focus of computers from buildings to human experience in buildings.

Today simulations are used in many areas of design to frame the performance of buildings in terms of sensations and human states of being. Lighting designers now address visibility, acousticians discuss the experience of envelopment, and fire engineers worry about how people might escape from burning buildings. Along with this new focus on the human response to building performance, Arup design professionals have adopted a new conception of human experience: that it can be objectified, replicated, and controlled.[281]

We can delaminate design narratives into genres. Each genre can be seen as a different layer, addressing a different rhetorical function. At the technical level, design narratives are tools for quantification. At the analytical level, narratives are devices for problem solving. At the methodological level, narratives are devices for the organization of work. At the reflective level, they are tools of self-analysis. These layers can be seen as a nested hierarchy; each layer is a reflection on the previous layers of narrative. For example, new technical narratives developing around simulations have changed the way designers reflect on their identities as professionals.

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[281] The objectification of experience by design professionals is not new. however. See William Ivins, *On the Rationalization of Sight, with an Examination of Three Renaissance Texts on Perspective.* Ivins explains how modern notions of sight developed in Renaissance Europe through the invention of linear perspective. The perspectival system is a framework for creating optical consistency among images. It allows artists to construct fantastic images that share the same structure as representations of nature. Through the use of perspective, fantasy can appear as believable as reality. Since the Renaissance, rationalization has been extended to many other areas of perceptual and spatial experience.

Technical narratives are stories about the mechanics of building design. Technical narratives can be about the origins of simulation technologies. They can be about the scientific models and empirical data which underlie these technologies. Technical narratives can also be about the interfaces and interactions through which designers encounter technologies for simulation.

> *Example of a Technical Narrative:*
> Fablon works on the principle of dynamic relaxation, developed by Alistair Day, an Arup engineer and academic, in the 1970s. Some of Day's papers on the subject can be found in old engineering journals, like "Air-Supported Structures" from *The Journal for the Institute of Structural Engineers*, published in 1980. Dynamic relaxation was originally developed to perform non-linear analysis on the foundations for nuclear reactors. This technique uses an iterative approach to resolve the relationships among a number of independently defined elements. It has since been adopted as a technique for form-finding in cable and fabric structures. It would work for any non-linear structure.[282]

Analytical narratives are stories in which technologies for simulation are used to reason about particular designs. These narratives are often about spatial conditions in buildings. Analytical narratives may be developed to argue for an optimal design, to bypass prescriptive regulations, or to lower the risk involved in a complex design. Analytical narratives are sometimes referred to as "scenarios" by designers at Arup. It is within these scenarios that simulations are given appropriate inputs and generate interpretable outputs. Scenarios are the stories by

[282] Tristran Simmonds, interview by the author, 2007.

which design professionals organize their thinking about how best to solve a particular design problem. A scenario is a highly-specific, numerically-supported, narrative that illustrates the properties of a design. Form example, a scenario might describe the amount of time necessary for an "average" person to escape from the fifth floor of a burning building. Analytical scenarios are developed as a consensus among designers and clients and usually tailored for a specific audience. A scenario is a means of describing the dynamics through which a contested set of design concerns is made subject to quantitative methods of evaluation.

> *Example of an Analytical Scenario:*
> 9/11 was an unheard-of scenario. However, the day after 9/11, it was immediately in everyone's mind as a scenario. For instance on the IFC2 building in Hong Kong, we were halfway to completion when 9/11 happened. The day after, the client wanted to know if it was going to be safe, would anyone want to occupy the upper stories? News events are often the source of new scenarios. These are the events on client's minds. When the suicide bombing happened in London, that became a scenario. Our security business has been very busy. Another current scenario is infection control in hospitals. This is a problem for airflow. This scenario is on the top of the agenda for the National Health Service. In high risk cases like this, even the most crude simulation might be better than nothing. More people are dying in the hospitals than on the roads.[283]

[283] Tony Sheehan, interview by the author, 2007.

Methodological narratives explain how simulations fit into a broader design process. Unlike analytical narratives, methodological narratives are not about specific projects. Methodological narratives are explanations of how simulations are (or should be) used. These stories are useful for understanding how simulations challenge the way designers organize their work and distribute design tasks among themselves.

> *Example of a Methodological Narrative:*
> Every single aspect, if you start thinking about how the outside noise relationship relates to the inside noise relationship, how the design of this partition relates to how much sound goes from room to room, what the acoustics of this room are like. Every element of that can be broken down, can be explained, can be subjectively value engineered. The term value engineering is a misnomer because people will try to reduce the cost of something, but that often means putting a value on whether something is necessary or not necessary in a design.[284]

Reflective narratives are stories in which design professionals invoke simulation in the course of their reasoning on design as a domain of work. These reflections may address the purposes of design, what makes a good design, or what it means to be a designer. Such narratives reveal how professionals see themselves and their work in the context of simulations.

[284] Raj Patel, interview by the author, 2006.

> *Example of a Reflective Narrative:*
> Architects and engineers are at war. Engineers are perceived as the dumb guys. Architects are the artists. I couldn't understand this position. Now I am working almost as another architect. I focus on building rather than engineering or architecture. I tells the people that work with me that you have to learn the language of architecture. Talk in terms of texture and density, instead of torsion and shear. That way they don't think you are just another nerd.[285]

In my own writing, I'm using another recognizable narrative model, the cultural narrative. My cultural narratives attempt to account for the role of simulation in the construction of meaning in design. Cultural narratives are no truer than the stories that design professionals tell. The goal of my writing is to present a novel framework through which people outside of Arup might gain insight into how design practice is changing along with information technologies for simulation.

Simulation as Theatre

In professional narratives about simulation, practitioners at Arup often invoke discourses on performance, scenarios, audiences, and the dynamics of human experience. There is an implicit metaphor in these discourses that simulation is theatre. One might say that through simulations, professional narratives take on a theatrical quality. This metaphor has lessons beyond these

[285] Cecil Balmond, interview by the author, 2007.

few useful terms for dealing with simulations. Taking the metaphor that simulation is theatre seriously opens new questions: what kind of theatre is simulation?

The early twentieth-century German playwright and theorist Bertolt Brecht juxtaposed two types of theatre: dramatic and dialogical (what he originally called epic theatre).[286] Brecht's juxtaposition can be helpful in understanding the different ways that Arup uses simulation to engage clients, collaborators, and regulators as audiences.

Brecht is motivated by a dissatisfaction with the dramatic theatre; he considers it a place of passivity for audiences. Brecht describes performance in the dramatic theatre was an integrated experienced which envelops the audience. Music, text and the visual arts contribute to what the German opera composer, Richard Wagner, called *gesamtkunstwerk* or total theatre. Brecht fears that the dramatic theatre tries to universalize experience. It does not challenge audience members to examine the structure of experience and performance; it leaves them complacent.

In contrast, Brecht proposed the dialogical theater as a place of rational dialog among audiences and actors. In contrast to total theatre, the dialogical is an experience under construction. Music, text, and visual arts are disassociated in the dialogical theatre. David Krasner writes, "[Brecht] wanted spectators to reflect on the staged event, consider how it took shape in reality, and explore what can be done to change the course of events."[287]

Reflecting on the use of simulations at Arup, we can see connections to both the dramatic and the dialogical theatres. Using simulations in a dramatic

[286] Architectural theory has of course made use of Brecht's work. In *House III* Peter Eisenman presents a dialogical building, in the tradition of Brecht. Eisenman uses Brecht to think about how architecture might be experienced from a critical perspective.

[287287] *Theatre in Theory, 1900-2000*: An Anthology, ed. David Krasner (Oxford : Blackwell, 2008).

fashion could mean that audiences -- architects, developers and building regulators -- understand designs through the experience of simulation, a kind of virtual reality. Virtual experiences of a buildings are produced through the manipulation of what Baudrillard has called "signs of the real."[288] Signs of the real are visual, auditory, or other sensory cues which form the basis of a simulated reality. Like the dramatic theatre, virtual experiences present themselves as holistic. In the dramatic theatre, a holistic or "total" theatre experience is constructed through the integration of music, text, and visual arts. The German opera composer Richard Wagner called this integration of the arts *gesamtkunstwerk.*[289] The same German term has been appropriated to describe a holistic or "total architecture."[290] It is interesting to note that the concept of total architecture, first written about by the German architect, Walter Gropius, and later embraced by Ove Arup probably also had its roots in *gesamtkunstwerk.* At Arup, the of integration of design disciplines is still referred to as total architecture. Through the lens of simulation, the pursuit of total architecture at Arup has become a pursuit of integrated performance, in technologies like Realtime, an immersive environment being developed in Arup's Foresight, Innovation and Incubation Group. Realtime combines performance from acoustics, lighting, airflow, and structures.

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288 Jean Baudrillard, *Simulacra and Simulation*, trans. Sheila Faria Glaser (Ann Arbor: University of Michigan Press, 1994).
289 *Theatre in Theory, 1900-2000: An Anthology.*
290 Complete Reference.

Brecht on Theatre (1918-1932)

Dramatic Theatre	*Epic (Dialogical) Theatre*
plot	narrative
implicates the spectator in a stage situation	turns the spectator into an observer, but
wears down his capacity for action	arouses his capacity for action
provides him with sensations	forces him to take decisions
experience	picture of the world
the spectator is involved in something	he is made to face something
suggestion	argument
instinctive feelings are preserved	brought to the point of recognition
the spectator is in the thick of it, shares that experience	the spectator stands outside, studies
the human being is taken for granted	the human being is the object of the inquiry
he is unalterable	he is alterable and able to alter
eyes on the finish	eyes on the course
one scene makes another	each scene for itself
growth	montage
linear development	in curves
evolutionary determinism	jumps
man as a fixed point	man as a process
thought determines being	social being determines thought
feeling	reason

Figure 27. Brecht's juxtaposition of the dramatic theatre and the dialogical theatre. Bertolt Brecht, *Brecht on Theatre: The Development of an Aesthetic*, ed. and trans. John Willett (New York: Hill and Wang, 1964).

In contrast, the dialogical theatre establishes a critical distance between the components of the performance; music, text, and visual arts are dissociated. Brecht's dialogical plays present the theatre as an experience under construction. Similarly at Arup, simulations are sometimes presented as under construction. Arup fire safety engineer, Peter Bressington notes that it is sometimes healthy for simulations to be presented as distinct and in conflict. From Bressington's point of view, integration can happen through discussion and reflection on the various components of simulation. For critical and dialogical purposes, integration is problematic; it masks the integrity and structure of individual simulations. Analysis often works best when it is used to isolate and examine a particular phenomenon like airflow, acoustics, structures, or lighting. Integrated simulations are dramatic. They can create a holistic experience for audiences, but that experience is inscrutable.

Furthermore, Brecht writes that the audience should be distanced from the performance. He called this the *verfremdungseffekt*, an estrangement or alienation effect meant to induce critical though. Brecht wants audiences to approach theatre rationally, rather than through uncritical experience. Audiences of the dialogical theatre are made aware of the "fourth wall" of the stage, the invisible barrier that in the dramatic theatre separates actors from audiences.[291] The result, writes Brecht, is that rather than rendering the audience complacent, the dialogical theater "arouses the capacity for action."[292] The implications for simulation are that design can become a "what-if" game in which the audience is implicated in the making of decisions. This position is already evident in the way several members of Arup talk about the responsibility of simulation. Chris Kaethner of

[291] Bertolt Brecht, *Brecht on Theatre: The Development of an Aesthetic*, ed. and trans. John Willett (New York: Hill and Wang, 1964).
[292] Ibid.

Oasys argues that good simulations, their graphics, interfaces and manipulability, encourage more interrogation of what's behind the software.[293]

The metaphor that simulation is theatre can also reveal something about the construction of professional identities in design. The identity of characters in the dramatic theatre is unproblematic in one respect: the actor is the character. In the dialogical theatre, actors reflect critically on their roles, even while they play them out. They may even go so far as to comment on their characters in the third person. Brecht writes, "The actors too refrained from going over wholly into their role, remaining detached from the character they were playing and clearly inviting criticism of him."[294] In order to have an open, dialogical use of simulation in design, professionals need to reflect critically on their roles and relationships. Opening these roles and relationships to explicit discussion and negotiation can elucidate the conflicting perspectives on simulation.

Arup's simulations have both *dramatic* and *dialogical* aspects. Audiences of a simulation are both immersed and distanced from designs. Arup challenges audiences to approach designs emotionally as well as rationally. The production of building performance through simulation -- the design of analytical scenarios, and the representation of human experience in buildings -- is a balance between immersive and critical ways of engaging with audiences. The metaphor of the theatre reveals the importance of audiences in the practice of simulation. Creating a valid simulation at Arup, like creating a successful theatrical performance, is all about connecting with your audience in the right way.

In simulations which is both immersive and distancing, conceptions of design -- knowledge, form, and identity -- are juxtaposed. For example in the simulations of Stansted Airport, Arup presented regulators with knowledge

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[293] Chris Kaethner, interview by the author, 2007.

[294] Bertolt Brecht, *Brecht on Theatre: The Development of an Aesthetic*, ed. and trans. John Willett (New York: Hill and Wang, 1964), 71.

through the immersive experience of the animation, but also through discussion and critical reflection about the underlying evidence and algorithms. In the example of the Wexner Center for the Arts, Arup issued a report to the administration of the museum which described form as both an integrated performance and as a set of dissociated components. By showing both the dramatic and the dialogical perspectives on the Wexner, Arup illustrated how performance would be improved by changing some of the components of the museum, like its facade and mechanical systems. In the design of concert halls like Alice Tully Hall in New York City, Arup acousticians present themselves as playing multiple roles, or taking on a dynamic identity; they are both scientists and co-designers. They have a grasp on the technical underpinnings of the physics of sound, but they can also collaborate with designers on aesthetic decisions. The Sound Lab embodies this dual dynamic of the dramatic and the dialogical most poignantly. It immerses audiences in acoustical experience and then let's them step back and look at how that experience is constructed; both emotional and critical thinking are involved. Arup reaches many audiences by presenting simulations which balance the dialogical and the dramatic; they use simulations to engage their audiences critically, but also to make them feel comfortable.

I should acknowledge that the metaphor of the theatre breaks down easily. We should not confuse simulation with theatre. Audiences in the theatre and in simulation differ greatly. The audiences of simulation are often more involved in establishing the premises upon which performance is based. In addition, the makers of simulations are routinely their own audiences; practitioners often make simulations for themselves. Furthermore, simulations do not simply operate on the dramatic and dialogical level, they also offer room for other perspectives on an issue. Simulations allow design participants to circle around an issue and tinker with its premises.

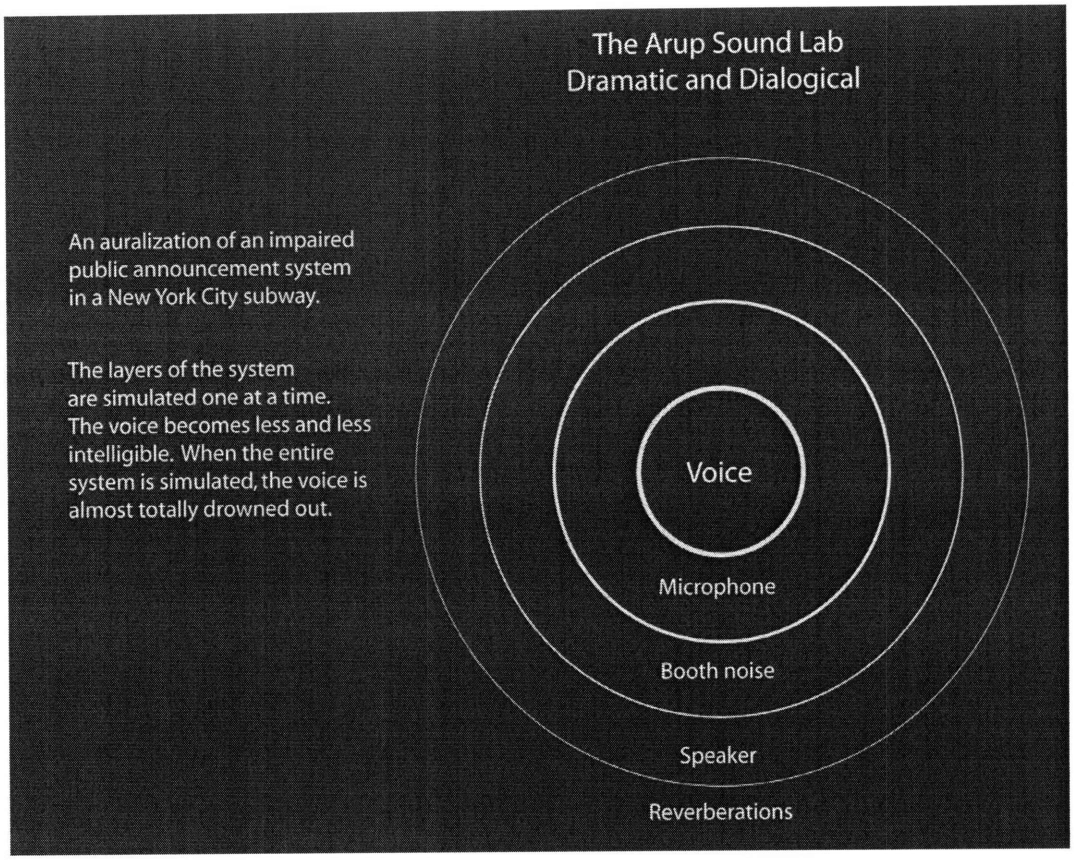

Figure 28. The sound lab embodies aspects of both the dramatic and the dialogical theatre. Through this simulation, an impaired public announcement system in a New York City subway can be examined dramatically, as one immersive experience, or dialogically, as the components of experience. Image by author.

Simulations open up spaces of exchange in which design participants can think and interact in new ways. The metaphor of the theatre allows us to see how simulation brings design discourse into the realm of the experiential in new ways. As spaces of exchange, simulations might be thought of as theatrical spaces, in which weighty themes like form, knowledge, and identity are re-examined by participants in the design process.

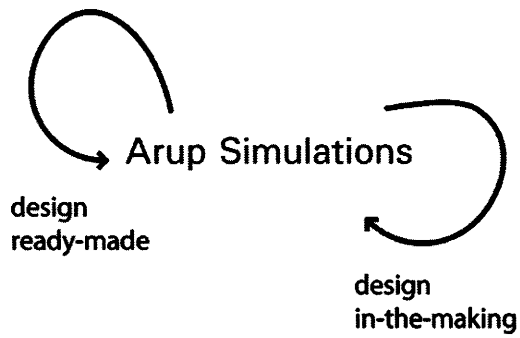

Figure 29. Simulation as theatre. Image by the author.

I should note that for Brecht, the theatre was more than mere entertainment or education. He saw the dramatic and dialogical theatres as social systems, supporting contradictory political agendas. Brecht developed his theory of the theatre during the 1930's in Germany. He believed that the dramatic theatre supported complacency among the public. In National Socialist Germany, the dramatic work of Wagner produced a kind of nationalism, that Brecht was wary of. Brecht's model of the dialogical was meant to combat over-exuberant nationalism by pushing the audience, particularly the proletariat, to think and to question their condition in society. Brecht's dialogical theatre was meant to be a catalyst not only for reflection but for revolution.

This dissertation is written for its own time and political climate. I do not see dramatic and dialogical uses of simulation in terms of nationalism. However, simulation can still be political. For example, simulations which account for human experience in buildings take on the responsibility of representing the public and their needs. By representing people, simulations speak for them. These simulations are used by practitioners to challenge established building regulations and the politics that underlie them. As practitioners continue to use simulations to represent the public and overturn building regulations, they have an imperative to adopt a broader discourse about politics in the discourse of design. Politicians, likewise have an imperative to engage design discourse. In *Science in Action,* Bruno Latour writes about how to take apart scientific and technological black boxes like simulations for political purposes.[295] He encourages us to engage "science in-the-making" as opposed to "science ready-made."[296] Similarly, I believe that seeing simulations not just dramatically, but as dialogical performances, as design "in-the-making," can encourage new critical discourses about design.

[295] Bruno Latour, *Science in Action.*
[296] Ibid.

CHAPTER 5 CONCLUSION

Conceptions of Design

My dissertation tracks varying conceptions of design through accounts from practitioners at Arup. These accounts reveal that differing conceptions about what design does, how it is done, and who can do it are often negotiated and reconciled through the practice of simulation. I have examined variations in conceptions of design along two dimensions. One dimension of my study tracks the diversity of meanings for design. Design can be seen in a multifaceted way: as a knowledge practice, as form, and as a profession. The other dimension of my study tracks the diversity of conceptions within these facets, among individuals and disciplinary groups. By studying design along these two dimensions, I have focused on different aspects of design, knowledge, form, and professional identity, as sites of contested meaning. In this chapter, I will revisit a few salient collaborative design projects at Arup, each focusing on one of these facets, in order to summarize how conceptions of design are expressed, negotiated and resolved at Arup through simulations.

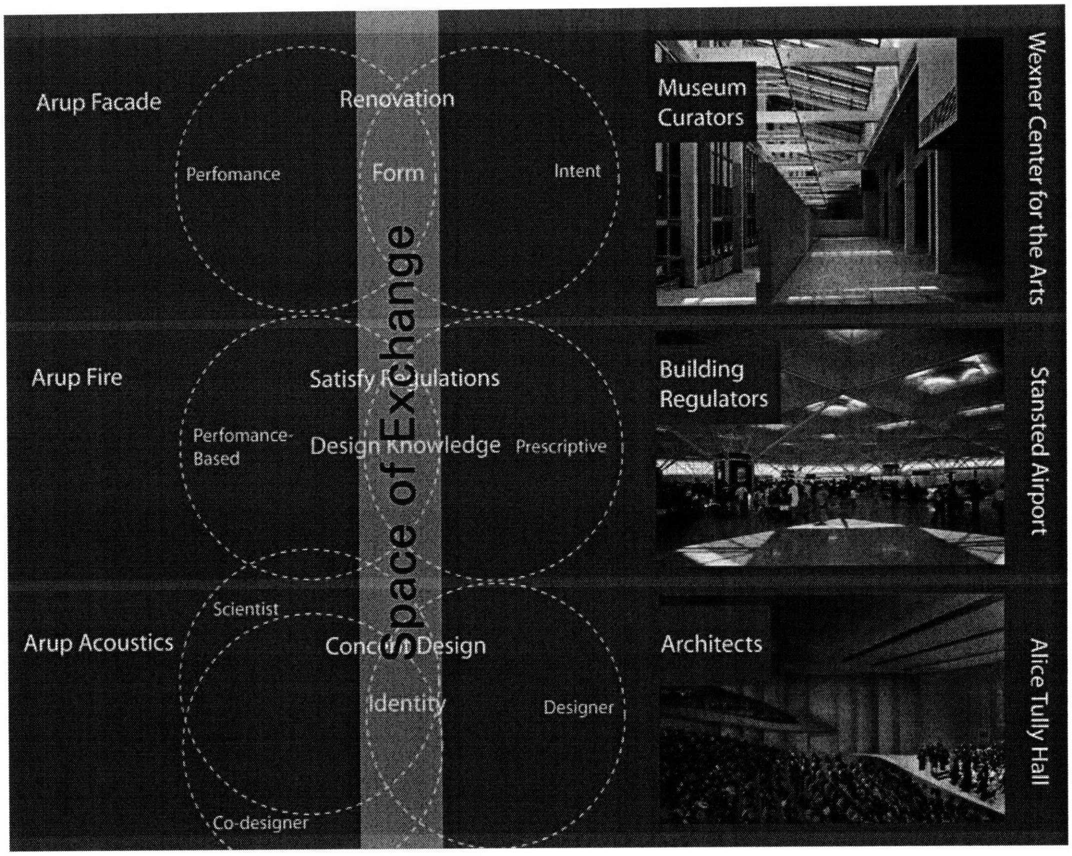

Figure 30. Negotiating Design. This diagram presents simulations as spaces of exchange which bridge between the technical domains of practitioners at Arup and the requirements of their clients, collaborators, and regulators. Image by the author.

Conceptions of Knowledge

In accounts about the design of Stansted Airport in England, I examined two conceptions of design knowledge at odds. Under the direction Margaret Law, Arup's fire safety group tested the conception that experiencing a design through simulation is an effective measure of its safety against standard knowledge about fire safety outlined in the local fire regulations. Regulations represent what Peter

Bressington calls a "prescriptive" approach to design knowledge.[297] In contrast, he champions a "performance-based" approach: knowledge expressed through simulation.[298] By distinguishing between prescriptive and performance-based knowledge, Bressington is not only articulating two ways of knowing, he is suggesting a broader distinction between an old culture of knowledge embodied by regulations and a new performance-based culture of knowledge at Arup. Prescriptive knowledge is used by regulators to establish homogeneous standards of safety which can be broadly applied. Performance based knowledge enables Arup to bypass these standards when they overly constrain the singular design of a client. These two expressions of design knowledge, regulations and simulations, are not easily reconciled. Bressington describes this process as "coming to a compromise."[299] The knowledge of regulations and the knowledge of simulations is reconciled in a "bargaining area." This bargaining area can be seen as an example of what I have been calling a space of exchange. In the case of Stansted Airport, the computer graphics simulation was an integral part of the exchange between Arup Fire and the regulators. Arup's simulation allowed regulators to virtually experience Stansted in a fire. Within the virtual building, regulators were able to reconcile their needs for prediction, control and narrative coherence with those of Arup's Fire Group.

Peter Bressington's account of the division between prescriptive knowledge, embodied by fire safety regulations, and performance-based knowledge, enabled by simulations, is an acknowledgement of a culture of simulation at Arup. He is dismissive of fire safety regulations, because they do not satisfy the needs of his epistemological culture. Regulations do not acknowledge the contingencies of experience in the same way as simulations. "In

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[297] Peter Bressington, interview with the author, 2007.
[298] Ibid.
[299] Ibid.

a fire, everything is transient."[300] The variable, performative aspect of simulations allows Bressington's Fire Group to account for different patterns in different places. Regulations homogenize design. The Arup Fire Group challenges regulations by appealing to the local contingencies of knowledge revealed by performance-based simulations.

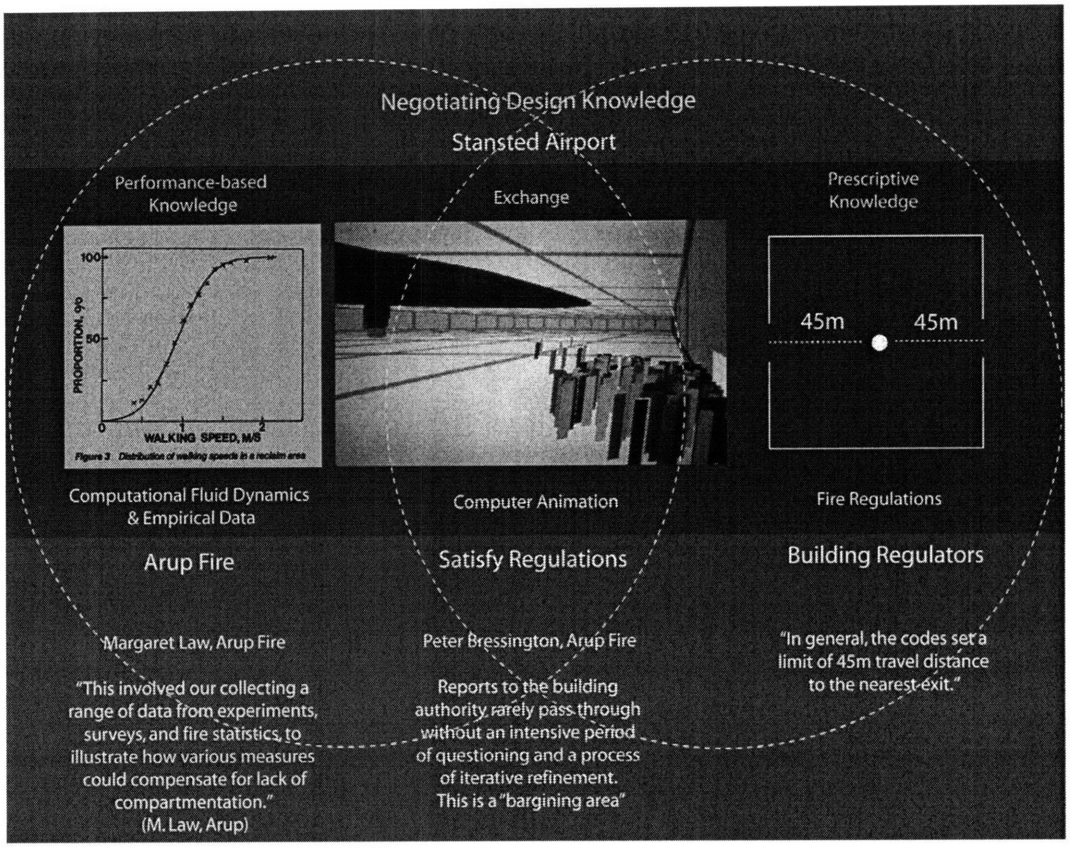

Figure 31. Negotiating Design Knowledge. This diagram presents the case of Stansted Airport, where a computer animation acted as a space of exchange between Arup Fire and building regulators. Image by the author.

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300 Ibid.

Conceptions of Form

Two differing conceptions of form had to be reconciled when Arup participated in the collaborative design of the Opera House in Sydney. Accounts from both Arup and Utzon about how the Sydney Opera House roofs were resolved provide useful evidence through which we can learn about how design professionals collaborate around simulations. Ove Arup and his team were concerned with structural performance, and at the heart of this, the calculability of form through mathematics. Utzon's team expressed aesthetic and expressive aspirations for the form, through drawings and physical models. These divergent goals were finally resolved by the shared use of spherical geometry. Although Utzon and Arup maintained their individual perspectives, they converged around this spherical geometry as space of exchange. The spherical geometry of the Opera House roofs allowed for both the engineers' and the architects' evaluation of form to be satisfied. For Arup, the spherical geometry represented a standardized, rational set of shapes that were calculable; their structural performance could be analyzed. For Utzon, the spherical geometry served aesthetic goals; it produced a compositional "harmony" among the shells.[301] Through the adoption of a spherical geometry as a space of exchange, their two divergent aspirations for the form of the roofs, calculability and harmony, were reconciled in one form.

Today, professionals at Arup still use simulations to evaluate form in terms of performance. Take the example of Arup's renovation of the Wexner Center for the Arts. The Wexner presents an extreme disconnect between two meanings of form. As a concept, the form was highly praised. However, it's performance was unacceptable by the museum administration. Arup's simulations demonstrated that by making subtle changes to the form, primarily to the facade

[301] Ibid.

and mechanical systems, a stable performance could be produced for the artwork and the visitors without disrupting the original intent of the form. Professionals at Arup explain the form of the Wexner as having two aspects, which can be treated independently. The concept or intent of form is the domain of architects. Arup takes responsibility over another aspect of form, its performance.

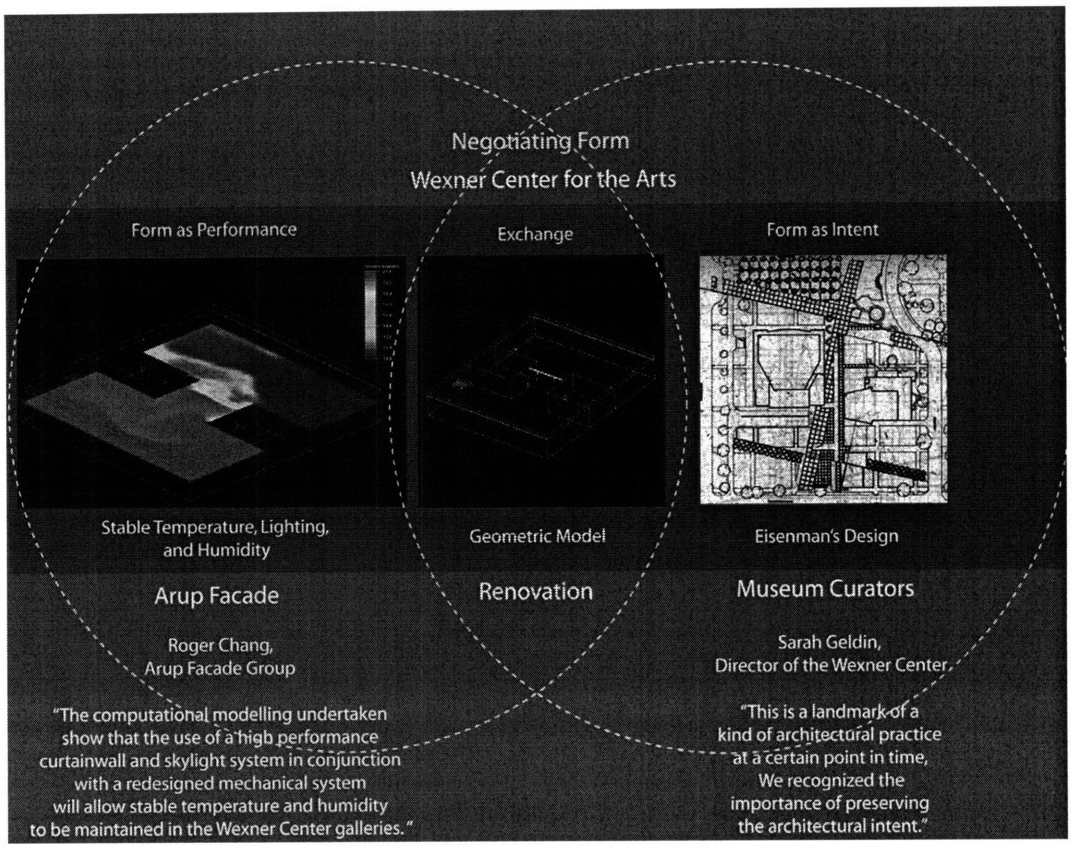

Figure 32. Negotiating Form. This diagram presents the case of the Wexner Center for the Arts, where a geometric model acted as a space of exchange between Arup Facade and museum curators. Image by the author.

Conceptions of Identity

Even within individuals, I have explained that there are varying conceptions of design at play. Accounts from Richard Sturt depict an ambivalent identity amongst professionals at Arup. Sturt contrasts two approaches to the development of simulations for design. One approach, which he terms "pragmatic," is focused on what users need and how they are going to use the simulation. An alternative approach is more "academic" says Sturt. The academic approach is to represent the intrinsic properties of construction materials used in a design, rather than relying on the simplifications defined in regulations. We mix and match these approaches, says Sturt.

Sturt's account calls to mind Max Weber's discussion of professional identity in his writings on science and politics as vocations. Weber contrasts the scientist's "ethic of ultimate ends" with the politician's "ethic of responsibility." When professionals at Arup forgo the tedious practice of modeling and simulate the expected effect, they are following an ethic of responsibility as opposed to an ethic of ultimate ends. From one project to the next, professionals at Arup can be seen to move between conflicting conceptions of identity. Sometimes they play the pragmatist, sometimes they play the academic. Sturt explains, "the right approach comes out of creative conversations you have with those on a project team."[302] Professional identity at Arup is often expressed and negotiated through practices of simulation.

Meanwhile, Arup's Acoustics Group in New York City, directed by Raj Patel is constructing new professional identities in the sound lab. Before the development of the sound lab, acousticians evaluated the acoustical quality of designs primarily using the Sabine formula. According to Patel, Sabine set up a narrow zone of interaction between acousticians and architects. The Sabine formula was by developed as a pursuit of science directed to a problem of design. Wallace Sabine and other early acousticians who employed his formula followed an "ethic of ultimate ends." As historian Emily Thompson explains, acoustics in

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[302] Richard Sturt, interview by the author, 2007.

the modern era was focused on optimization, finding the one best sound. In contrast, the sound lab enables a range of acoustical experiences to be explored, analyzed, compared and tinkered with. In the sound lab, design participants pick and choose but also tinker with the acoustical experiences that simulations define for them. By inviting architects, clients, and other collaborators into the process of evaluating acoustics, Arup is embracing a new legitimacy for acoustics, based on consensus. In the sound lab, Patel and his fellow acousticians balance their identities as scientists, with a new identity where the means, developing a consensus among design participants, is more important than finding an optimized solution. Although acousticians at Arup are trained as scientists, they have embraced an "ethic of responsibility."

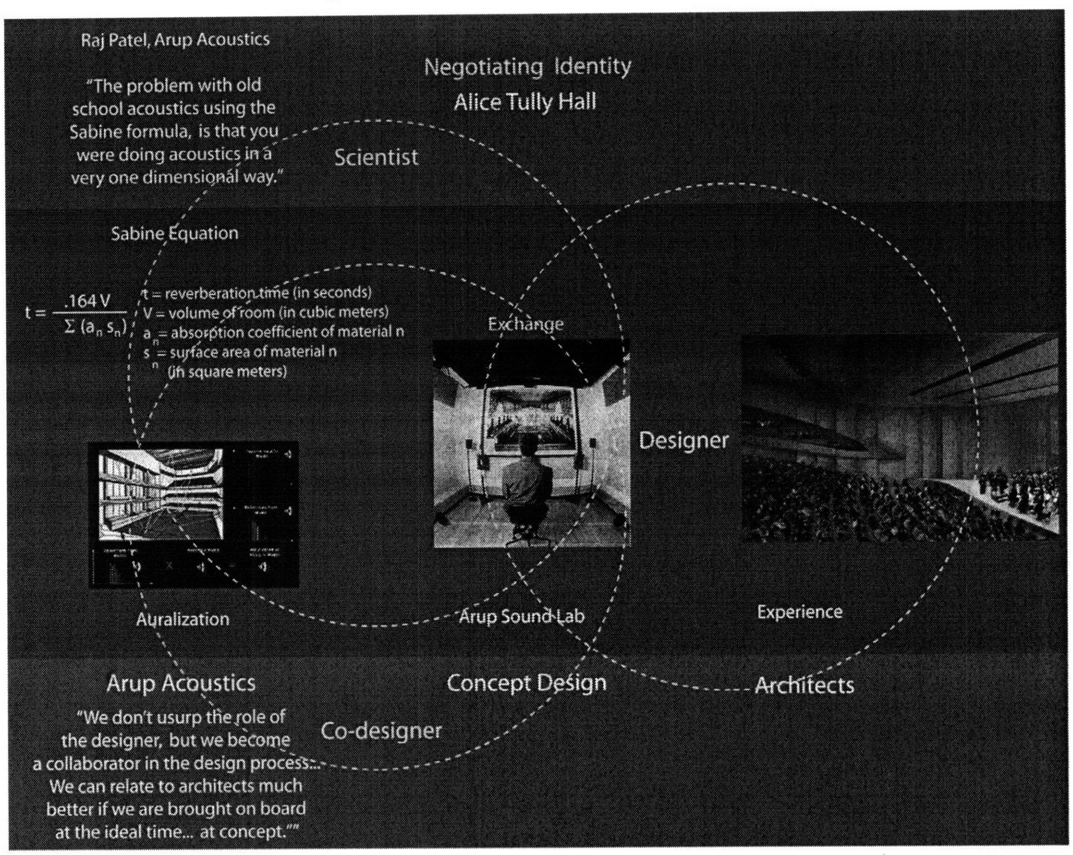

Figure 33. Negotiating Identity. This diagram presents the case of Alice Tully Hall, where the sound lab acted as a space of exchange between Arup Acoustics and architects. Image by the author.

Coda

In each facet of design explored in this dissertation, knowledge, form, and professional identity, I have found varying conceptions of design to be resolved in accounts about collaboration and compromise through simulations. Simulations are spaces of exchange in which design participants work out designs as well as loftier conceptions of what design means.

Arup has been successful in creating places for itself in design projects around the world by learning to engage a variety of clients in individualized ways. My dissertation illustrates how the firm has made use of simulations to mediate relationships with different architects, developers, curators, and building regulators. At Arup, simulations are designed to be spaces of exchange; they bridge between the technical requirements of engineers and scientists and the particular functional, aesthetic, or economic needs that clients, collaborators, and regulators bring to projects. The simulations that I have studied at Arup are made to be both technologically defensible and culturally palatable. However, practices of simulation at Arup are more than a means of communication. In order to position themselves professionally, Arup practitioners must distinguish themselves. Arup uses simulations to not only connect to other participants in design, but to establish their own distinct conceptions about design.

In this chapter, I have revisited the most salient distinctions introduced in my dissertation; between the prescriptive knowledge of building regulators and Arup's performance-based approach to knowledge; between the intent of form, attributed to architects, and the performance of form, revealed by Arup's simulations; and between the Janus-like identities of Arup practitioners, who embrace both the objectivity of scientists and the aesthetic interests of designers. These juxtapositions in conceptions knowledge, form, and identity underlie

Arup's efforts to create places for itself in design, both professionally and ideologically.

This study of simulation at Arup builds on a history of scholarship by writers like Lewis Mumford, Sherry Turkle, and Peter Galison, who examine how cultures define themselves through the technologies they use and the way they use them. My contribution to this discourse has been to illustrate how designers use simulations to establish the professional relationships and the conceptual distinctions that define their work. In the process, I have developed an empirical framework for dealing with simulation. I treat the meaning of simulation as dynamic. Simulation is a varied practice at Arup, used to create diverse spaces of exchange with clients, collaborators and regulators. This study has also given me an opportunity to develop my own particular socio-technical approach to the study of design culture. Through this approach, I have identified controversies in design practice over conceptions of knowledge, form and professional identity. These are controversies which can benefit from further research. I hope to continue refining and testing my socio-technical approach to design by studying other cultures of practice.

List of Figures

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